MULTI-INSTRUMENTAL AURORAL

CASE-STUDIES AT SUBSTORM CONDITIONS

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Academic Dissertation to be presented with the assent of the Faculty of Science, University of Oulu, for public discussion in the Auditorium L10, Linnanmaa, on September 30\textsuperscript{th}, 2005, at 12 o’clock noon.
"... So sind wir zwar nicht mehr in der glücklichen Lage Keplers, dem der Zusammenhang der Welt im großen durch den Willen ihres Schöpfers gegeben war und der mit der Erkenntnis der Sphärenharmonien schon dicht vor dem Verständnis seines Schöpfungsplanes zu stehen glaubte. Aber die Ahnung eines großen Zusammenhanges, in den wir mit unseren Gedanken doch schließlich immer weiter eindringen können, bleibt auch für uns die treibende Kraft der Forschung."

Final paragraph of Werner Heisenbergs lecture at University of Leipzig at November 26., 1941: "Die Einheit des naturwissenschaftlichen Weltbildes".

to my family
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Multi-instrumental auroral case-studies at substorm conditions
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Abstract
The general aim of the present study is to gain insight into physical mechanisms of some auroral forms on the basis of multi-instrumental measurements (satellites, rockets and ground-based magnetic and riometer instruments) in the vicinity of the auroras observed by ground-based all-sky cameras.

One part of this work is related to the Auroral Turbulence II sounding rocket experiment. It was launched on February 11th, 1997, at 08:36 UT from Poker Flat Research Range, Alaska, into a moderately active auroral region after a substorm onset. This unique three-payload rocket experiment contained both electric and magnetic field and particle instruments, which provided three-point measurements over a wide scale length. With this experiment in the evening sector (21 MLT), auroral forms at the substorm recovery were investigated, providing details of the quiet and disturbed auroral fine structure. The rocket data are compared with ground-based optical and magnetic measurements. Special emphasis is devoted to field-aligned current densities and DC electric fields of a large quiet arc traversed in the middle of the flight. Another topic of interest are the disturbed auroral arcs with bright patches propagating along them like a luminosity wave. Those evening auroral patches and associated electric fields formed a 200-km spatially-periodic structure along the arc, which propagated westward at a velocity of 3 km s⁻¹.

The other part of this study describes ground signatures of dynamic substorm features observed by the IRIS imaging riometer, magnetometers and all-sky camera during late evening hours. The magnetometer data were consistent with the motion of upward field-aligned currents (FAC) associated with absorption patches moving within the field of view of the riometer. Riometer data are used to estimate the intensity of FAC associated with these local current-carrying filaments. It is shown that, during these events, the estimated FAC intensity exceeds a threshold value, which corresponds to the excitation of the low-frequency turbulence in the upper ionosphere. As a result, a quasi-oscillating regime of anomalous resistivity on the auroral field lines can give rise to the burst-like electron acceleration responsible for simultaneously observed auroral forms and bursts of Pi1B pulsations.

Keywords: Auroral ionosphere, Electric fields, Auroral patches, Field-aligned current, anomalous resistivity
0.1 Preface

This work was carried out at the University of Oulu, Finland. I thank professors Rauno Anttila and Jukka Jokisaari, the former and present head of the Department of Physical Sciences, for placing facilities at my disposal. I would also like to thank all the staff of the same department and the Sodankylä Geophysical Observatory for their hospitality and help during all these years.

My deepest gratitude I would like to express to my former "Doktor-Vater" Prof. Jorma Kangas for opening my door to space (-physics) and for his unwavering support, of both scientific and personal nature. I would like to express my sincere gratitude to my present supervisors Dr. Tilman Bössinger and Dr. Kari Kaila. Also I am particularly indebted to my teacher and unofficial supervisor Dr. Alexander Kozlovsky, whose excellent and patient guidance has given me various theoretical ideas for my experimental studies. Without his and Dr. Tilman Bössinger’s steady support in all kinds of problems, big and small, at all stages of the work, and without their never-ending optimism and encouragement, this thesis might never have been completed.

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During the past years I have come to know my two main co-authors Dr. Sergei Shalimov (Institute of Physics of the Earth, Moscow) and Mr. Aarne Ranta (MSc, Sodankylä Geophysical Observatory) very well. From our common studies I learned more than only physics. They deserve many special thanks for our wonderful discussions at work as well as on leisure time occasions.

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Last but not least, I wish to express my deep thanks to my wife Virpi and my daughters Inka and Cassandra as well as to my dear parents for their
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0.2 List of original papers

This thesis is based on the following four original papers, which are referred to in the text by Roman numerals:


All of these papers were prepared together with co-authors. In Paper I, the present author took part in data analysis, e.g. by analyzing Polar satellite images in order to determine the large scale formation of the auroral structure around the rocket trajectory and by calculating the crossing angle and position of the payload cluster. In papers II, III and IV he carried out the main preparation of the manuscripts, a major part of the scientific analysis and interpretation as well as the preparation of the majority of the figures presented.

The other co-authors were involved in carrying out the rocket experiment and the related scientific discussion. The theoretical estimates in Paper II and III were suggested by the co-author Dr. S. Shalimov. In Paper IV, the co-author Dr. A. Kozlovsky was actively involved in the entire study. However, the data analysis codes and the data processing were provided by the present author.
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Chapter 1

Introduction

The Earth is one of the planets of our solar system which strongly interacts with the solar wind plasma. Solar wind was found by Biermann in the year 1951 and was proven many years later by space probe measurements. The modern idea that Earth is moving in an extended solar atmosphere and that solar particles enter the terrestrial atmosphere was first introduced by Mairan. Already in the year 1733 he used this hypothesis in his book to explain phenomena such as the aurora (aurora borealis and aurora australis) in Earth’s polar regions.

The geomagnetic field was recognized even earlier. In the eleventh century, a device for magnetic direction finding was brought to Europe from China, where it was already used for navigating. This very early "magnetometer" was the compass. In the sixteenth century, the magnetic declination was discovered as a result of the maritime navigation. At the same time William Gilbert described in the context of his magnetism studies the discovery of the magnetic dip (or inclination) and can be regarded as the first to suggest a "Terrella-model" (distribution of magnetic inclination over the Earth). However, he believed the terrestrial magnetic field to be constant. Already in the years 1722-23, a watchmaker from London named Graham found that the geomagnetic field is not constant. Humboldt introduced in 1808 the magnetic storms, which are still today a topic of intensive research in space physics. Finally Gauss discovered that a small fraction of the geomagnetic field measured at the ground has an extraterrestrial origin. Various significant observations followed Gauss’ discovery. However, it is only some half a century ago that mankind learned about the real condition of the near-Earth space environment and its interactions with solar wind plasma. This has been possible with the aid of satellite and rocket experiments.

In the absence of any external drivers and only considering the strong internal magnetic field of our planet, we may approximately observe a geo-
magnetic dipole field with its axis tilted by about 11 degrees from the Earth’s rotation axis. This simple picture is strongly modified due to the presence of the solar wind; a cavity called the "magnetosphere" (Figure 1.1) is created. Energy and momentum from the solar wind are transferred into the Earth’s magnetosphere. Magnetospheric electromagnetic fields and plasmas are strongly governed by this solar wind - magnetosphere interaction. It drives the magnetospheric convection system and maps down along magnetic field lines into Earth’s ionosphere. Spectacular phenomena like, e.g. the auroral display, occur in the polar upper atmosphere.

In the present work, four studies are presented to investigate phenomena related to auroral physics. Although in the past, a general scenario was found to explain quiet as well as disturbed auroral phenomena, we are still seeking detailed insight in the complexity of auroral phenomena on various scales.

While continuous measurements on the ground are readily available, continuous rocket or satellite observations are rare and expensive. Rocket observations are of narrow spatial scale, whereas the satellite in-situ measurements are limited to a given location at a given time. However, new imaging methods can give a very global view of the near-Earth space by satellite observations. Papers I and IV deal with auroral phenomena during the Auroral Turbulence II (AT-2) rocket experiment (Chapter 2.1). With the experimen-
Figure 1.2: The setup of the Auroral Turbulence II (AT-2) rocket experiment. There are ground-based TV observations as well as rocket and satellite in-situ measurements. The magnetic and electric field measurements are correlated with the optical auroral structure as seen by the ground-based observers (all-sky cameras and meridian scanning photometer).

The unique multi-instrumental setup used in the AT-2 rocket experiment (Figure 1.2), it was possible to study correlations between particles, magnetic and electric fields in auroral structures. Here, the general geophysical conditions are studied for the duration of the AT-2 mission. The physics of one particular auroral arc is studied. The FAC signatures are investigated and compared with the large-scale distribution (Iijima and Potemra, 1976a; Iijima and Potemra, 1976b). The multipoint rocket measurement is utilized in Paper I to study large DC electric fields and shears in the auroral zone. A quiet auroral arc was investigated and a region of highly localized, sheared and intense DC electric field was found.

The unique multi-instrumental setup of the AT-2 mission made it possible to investigate optical auroral structures together with rocket in-situ measurements at substorm recovery. The ground-based optical coverage of
rocket experiments is an almost standard procedure today. Their temporal and spatial resolution is increasing at present\(^1\). However, good ground-based optical observations together with rocket in-situ electric field measurements are still rare. Indeed, two recent studies of this kind were performed by Hallinan et al. (2001) and Maynard et al. (2000).

In Paper III, which was submitted and accepted before Paper II but published later, a connection between auroral activation and magnetic impulsive event (MIE) on the nightside is proposed. MIE was observed during the growth phase and onset of substorms in association of field aligned currents (FACs). The energy released in the plasma sheet during each activation is channeled down to the auroral ionosphere by FACs. This linkage between magnetospheric and ionospheric plasmas via FACs is thus important for the coupling of the magnetosphere with the ionosphere. Directly, monitoring FAC densities from the ground is not possible since they are magnetically invisible. This is because the curl-free part of the ionospheric current together with the FAC does not produce any magnetic field disturbance below the ionosphere. Methods for estimating FACs from ground-based measurements were developed in the past (Amm, 1995; Baumjohann et al., 1981; Inhester et al., 1992; Kamide, 1981). Usually, rocket or satellite measurements are used to measure FACs as well.

Paper II presents a new and easy method to estimate FAC densities in current-carrying filaments using ground-based measurements only. The only technical requirements are three instruments located in the vicinity of overhead FACs: i) an imaging riometer, ii) a normal magnetometer and iii) a pulsation magnetometer. In addition, auroral all-sky cameras are used to verify coinciding signatures. The method is used during disturbed geomagnetic conditions. These periods are i) substorm onsets when rapid changes are observed in the magnetic Z-component and ii) substorm intensifications. Verification on this method is given in Chapter 3.5.

In the following sections, the basic physics of the previously mentioned studies is outlined.

### 1.1 Cosmic noise absorption (CNA)

Investigation of CNA is done by riometers. A riometer (relative ionospheric opacity meter) is a radio wave receiver sensitive in the 20 to 50 MHz frequency range. Usually it is pointed towards the local zenith. There are simple wide beam riometers (which collect all signals from a wide antenna beam around local zenith) and imaging riometers (single narrow beams arranged into an

\(^1\)http://www.fmi.fi/tutkimus_avaaruus/avaaruus_48.html (online 2003- )
array). Newer riometer arrays (e.g. AIRIS at Alomar Observatory / Norway) have the ability that their beams may be tilted as required.

Ionospheric attenuation of high-frequency cosmic radio waves depends on the product of electron density and electron collision frequency, integrated along the path of propagation. The cosmic noise absorption, $A$ (in decibels [dB]) detected on the ground is given by the following simplified expression (see, e.g., Hargreaves, 1992, page 65):

$$A[dB] = 4.5 \cdot 10^{-5} \int \frac{N \nu}{\nu^2 + \omega^2} \, dx,$$

where all quantities are in SI units. The number density of charged particles is $N$, the collision frequency $\nu$, and the angular wave frequency $\omega$. The integration in equation 1.1 is along the path of propagation, $x$.

Among various reasons for absorption, the most common one at auroral latitudes is the precipitation of energetic electrons which cause an increase of electron density and ionization. Maximal absorption occurs typically at about 95 km.

The observations by imaging riometers (Hargreaves et al., 1997, Ranta et al., 1997) have improved the picture of substorm development. During CNA events, the substorm-related energetic electron precipitations may produce a slowly southward-moving absorption bay, which precedes the intense precipitation at substorm onset. This pre-onset signature was identified as an arc-like feature extending east-west across the entire field of view (Kamide, 1981, Ranta et al., 1983).

It appears now that the onset is due to an intensification within this arc, giving rise to CNA "spike events" of elliptical shape, with major axis generally along the L-shells, and with a duration of only a few minutes (Hargreaves et al., 1997). In the course of substorm development, the precipitation region may expand, with a sharp onset at the front towards the west in spatially confined regions at high ($L > 6$) and low ($L < 4$) $L$-values, both with roughly equal velocities (Ranta et al. (1983)).

### 1.2 Impulsive phenomena in the magnetosphere

Transient magnetic impulse events (MIEs) lasting for 5-15 min are frequently recorded by high-latitude ground magnetometers (Lanzerotti et al., 1991; Sibeck and Korotova, 1996). MIEs were previously explained in terms of the ionospheric response to transient magnetic reconnection at the magnetopause, commonly termed Flux Transfer Events (FTE) (Russell and Elphic, 1979; Glassmeier, 1984; Lanzerotti et al., 1986).
Initially, impulsive phenomena were studied at the dayside (Mozer et al., 1980) where the field lines on which the transient events occur in the ionosphere predominantly map to the dayside magnetopause. In this region they imply some type of impulsive solar wind/magnetosphere interaction. This is the reason for a steady interest during the last decade in the impulsive phenomena occurring in the magnetosphere and ionosphere. According to the initial suggestion (Lanzerotti et al., 1986), large-amplitude (> 100 nT) impulsive magnetic variations observed on the ground at high latitudes are due to Hall current vortices in the lower ionosphere associated with FACs. Several mechanisms have been proposed for the MIEs formation through FACs connecting the magnetosphere and ionosphere. They include variations in the solar wind dynamic pressure (Sibeck and Korotova, 1996; Yagodkina and Vorobjev, 1997), bursty merging at the magnetopause (Glassmeier et al., 1984), impulsive penetration of interplanetary plasma (Heikkila et al., 1989), and a Kelvin-Helmholtz instability acting at the low-latitude boundary layers (McHenry et al., 1990). It was found that these dayside magnetic variations are accompanied by the sporadic appearance of discrete aurora (Mende et al., 1990), riometer absorption (Korotova et al., 1999), and magnetic pulsations in PiB frequency range (Pilipenko et al., 1999). Especially the study by Pilipenko et al. (1999) was basic for Papers II and III in which nightside MIEs are studied.

It is generally accepted that communication of a magnetospheric disturbance, such as a FTE, to the ionosphere occurs through field-aligned currents which close in the ionospheric E region (Southwood, 1987; McHenry and Clauer, 1987). When reconnection commences at the magnetopause, solar wind plasma is linked to the ionosphere via convecting flux tubes which carry these field-aligned currents. The exact nature of the field-aligned current systems, and their closure currents in the ionosphere, as well as their closure and driving in the magnetosphere, is not well understood. However, the characteristic magnetic perturbations generated in response to the Hall component associated with the closure current have been extensively modeled, most recently by Chastain et al. (1993), Zhu et al. (1997), and Zhu et al. (1999).

The more common MIE is a transient dayside phenomenon, induced by steep variations of solar wind pressure or IMF orientation. Here, another class of MIEs is considered, which occurs on the nightside. These nightside MIEs is caused by another, still not established, mechanism which is probably related to the auroral activation. Statistical studies of high-latitude MIEs confirm that some of these events were observed in the nightside auroral oval (Lanzerotti et al., 1991; Sibeck and Korotova, 1996).

The magnetospheric location of the source of FACs is very important for
understanding the generation mechanism of MIEs at the nightside. However, it is difficult to map FACs into the tail as the current is strictly field-aligned only in the very low beta plasma above the auroral ionosphere, but spreads over a very wide domain when beta becomes larger (see, e.g., Janhunen and Käskinä, 1997, who were able to perform a MHD simulation of closure of Region-1 FAC).

In Paper II, the MIEs is observed on the nightside and inside the auroral oval. The aurora is most probably associated with the precipitation from the plasma sheet region (e.g. Vorobjev et al., 2003). The fact that the source of the FACs connected with MIEs is located inside the plasma sheet is supported by several studies (e.g. Ohtani et al., 1995). Although these connections seem to be supported by observations, their physical mechanisms have not been firmly established yet.

It is natural to associate these FACs with impulsive release of magnetotail energy that marks the onset of the substorm expansion phase. The typical signatures of the onset observed on the ground are the auroral breakup, initiation of P11 and P12 ULF pulsations and the appearance of a sharp negative H-component ("bay") (Akasofu, 1968). From all these observational characteristics, it follows that there are some threshold conditions (Nishida, 1990), and the magnitude of activation is determined by how much energy is suddenly released and dissipated in the system. We suggest that these threshold conditions are controlled first of all by the FAC densities connecting MIEs with the plasma sheet.

### 1.3 FAC connection between magnetosphere and ionosphere

The current that flows along field lines between the magnetosphere and the ionosphere is a key element in the physical coupling of those two regions. The highly complex mechanism of this coupling is sketched in the simplified picture (Figure 1.3). The magnetosphere is dominated by collision-free plasma. Collisions of charged particles with neutral particles are frequent in the ionosphere. Exchanging energy and momentum between the two regions is primarily carried out by the field-aligned currents. The magnetosphere-ionosphere coupling formed by the FACs is the reason for the response of all parameters in the loop (Figure 1.3).

One can start discussing Figure 1.3 at any point of the loop (e.g. B-C-D-A). Starting in the magnetosphere (B), one faces the current source (generator) region. The FAC connects to the ionosphere (C) and causes a
Figure 1.3: Logics of magnetosphere-ionosphere coupling (after Fig. 5.16. in Baumjohann and Treumann, 1997).

The voltage drop (D) which gives rise to the electric field, which maps back to the magnetosphere (A).

It is obvious that the electric field, E, and magnetic field, B, in the ionosphere (in-situ) have an impact to the whole magnetospheric-ionospheric system.

1.4 Wave propagation along the inner edge of the plasma sheet boundary

Two internal magnetospheric boundaries are important for the present study (Figure 1.1): i) the plasmapause (boundary of the plasmasphere; not indicated in Figure 1.1) and ii) the plasmasheet inner boundary. Furthermore, there may appear boundaries of different plasma regions within the magnetospheric plasmasheet. Surface waves along the plasmasheet inner boundary are of Alfvénic type (Safargaleev and Maltsev, 1986). A surface wave on a plasma boundary (e.g., the inner edge of plasmasheet boundary) can transports energy across the magnetic field lines and not along them (Maltsev and Lyatsky, 1984b).

Figure 1.4 (left side) sketches the propagation of a perturbation along the plasmasheet boundary (Maltsev and Lyatsky, 1984a). The initial perturbation at local midnight is divided into two, which travel symmetrically away
Figure 1.4: Propagation of a perturbation along a boundary. The figure on the left (Fig.1 in Maltsev and Lyatsky (1984a)) is an equatorial cross-section of Earth's magnetosphere. The figure on the right sketches a plasma sheet boundary with perturbation in the equatorial plane of the magnetosphere. Both sketches demonstrate the perturbation symmetrically moving away from its initial location to both the morning (East) and evening (West) sector.

into the morning and evening sectors with velocity $v_y$.

Figure 1.4 (right side) demonstrates how a perturbation at a plasma boundary (e.g. in the plasmasheet inner boundary) starts moving away symmetrically in two directions. The initial perturbation is polarized due to the electron and ion gradient drift motion towards east and west, respectively. As a result, a current, $j$, arises inside the initial perturbation, which leads to a polarization-potential electric field, $E$. The flanks of the perturbation are polarized and FACs appear. The polarization electric field causes the $\vec{v} = (E \times B)/B^2$ plasma motion that is directed against the plasma displacement in the initial perturbation. Thus, the initial perturbation tends to vanish.

At the same time as the initial perturbation is vanishing, two new perturbations are arising eastwards and westwards of it, leading to a wave motion. The group velocity of such a surface wave transverse to the magnetic field in the magnetosphere was estimated to be about 100 km s$^{-1}$, which corresponds to $\sim 5$ km s$^{-1}$ projected onto the ionosphere (Maltsev and Lyatsky, 1984a).

Earlier, it was suggested, e.g., that the absorption bay motion is a manifestation of an interaction between electrons and hydromagnetic waves (Hargreaves, 1968). However, it is possible that this hydromagnetic wave is in fact a surface wave on the plasma sheet inner boundary (Safargaleev and Maltsev, 1986).
Figure 1.5: Mechanism of discrete auroral development (Fig. 7.19. Prölss, 2004).

Upward field-aligned current is carried by a downward flow of electrons. When the electron flow exceeds a certain threshold magnitude, field-aligned potential differences may arise, which lead to electron acceleration and auroral luminosity. The field-aligned current density threshold value is of the order of $10^{-6}$ A m$^{-2}$ (Lyons et al., 1979).

1.5 Auroral ionosphere

First, it should be clarified that the auroral ionosphere has properties significantly different from those of the ionosphere at subauroral latitudes. For the disturbed auroral regions, particle precipitation (electrons) is the main ionization and heating source. Neutral particles are involved, e.g., in heat exchange whereas ions are relevant for Joule heating. Plasma transport is driven by electric fields.

Today it is well known (see, e.g., Meng et al., 1991) that auroral phenomena are generated by energetic electrons ($E_e \geq 1$ keV). Therefore electrons which have initially populated the plasma reservoir in the magnetospheric tail (with $E_e \leq 1$ keV) or the magnetosheath (with $E_e \leq 200$ eV) must be
further accelerated. This acceleration mechanism is not yet satisfactorily explained. However, in the following a widely accepted scenario (Figure 1.5) is assumed, based on field-aligned electric fields as the accelerating agent.

In order to produce a parallel E-field above the ionosphere, the FAC must produce a voltage drop in a regime of anomalous resistivity. During downward precipitation along the magnetic field lines, electrons are lost due to collisions as well as mirrored back due to the parallel component of the magnetic gradient force (so-called "mirror force", $-\mu \nabla || B$) at their mirror-point. In order to activate an upward current (carried by electrons), the mirror points of the electrons outside the loss cone have to be lowered in altitude. This happens due to a change in the electrons’ pitch-angle caused by the field-aligned electric field, $E_{||}$. The latter counteracts the mirror force and pushes additional electrons into the loss cone.

The field-aligned electric fields in the auroral topside ionosphere can be produced by various mechanisms: mirror resistance, dispersive Alfvén waves, double layers, etc. One of the most commonly discussed mechanisms is the occurrence of $E_{||}$ due to the anomalous resistance owing to plasma turbulence (Fälthammar, 1977).

1.6 Main goal of the present study

The main goal of this PhD work is to understand physical mechanisms for the generation of some auroral forms on the basis of multi-instrumental measurements. Many of these instruments are on the ground. However, they are supported by rocket in-situ and satellite measurements, as well. In addition, a new method is presented to estimate FAC densities from ground-based magnetic and riometer measurements.

The first topic of this thesis (Paper I) is devoted to stable auroral forms, including quiet nightside auroral arcs and evening-side (pre-midnight) arcs. The key problems under consideration are the electric field and currents associated with the arcs. These studies allow us to reveal mechanisms for these auroras and also to understand the connection of the arcs with global magnetosphere-ionosphere dynamics.

The second topic of this work (Papers II, III and IV) is devoted to unstable auroral forms such as arc fragments and auroral patches, which arise just after substorm onset and at the early recovery phase.

The third topic (Papers II and III) concerns transient magnetic impulsive events which are frequently observed at high latitudes by ground-based magnetometers.

A new technique (Paper II) to estimate the localized FACs has been de-
veloped using ground-based magnetic data combined with imaging riometer data. FACs estimates can be compared with other ground-based instrumentation (e.g. EISCAT radar or optical instrumentation) or with satellite data (Danielides et al., 2003). This comparison is important because the method requires proper scaling which can be achieved only by comparison with direct measurements of FACs. However, studies to obtain this scaling law directly are beyond the frame of the present thesis.
Chapter 2

Experiments

It is commonly accepted (e.g. Chapter 7.4.1 Prölls, 2004) that the visible auroras are produced mainly at low altitudes (at about 90-120 km), i.e., at altitudes where the atmospheric density is sufficient for collisions between electrons and other ionospheric particles to become significant. Arc structures have a perpendicular scale length from a few tens of km down to 100 m (Borovsky, 1989). To perform an experiment in the near-Earth space environment, it is essential to choose the best observational platform. A choice between a low-altitude satellite and a sounding rocket as the appropriate tool is based on the following arguments:

a) Low altitude satellites have short lifetimes due to atmospheric drag and degradation of materials. They have considerable launch costs and their orbits are not adjusted to suddenly occurring phenomena. Also, it should be recalled that a minimum orbital velocity of 8 km s$^{-1}$ is required. Then, e.g., an instrument sampling at 50 Hz can only resolve features larger than 160 m.

b) Sounding rockets have still a shorter lifetime than satellites. However, they are cheaper to build and launch. They collect a reasonable amount of data, which is still much less than satellites. Because of a flexible launch window they can fly into regions of specific interest at a preferred time. A ballistic flight to 300 km height has a platform velocity of 1 km s$^{-1}$. Then, e.g., an instrument sampling at 50 Hz resolves features larger than 20 m.

A sounding rocket experiment was the best solution for the AT-2 studies. Finally, the classical ground-based approaches are considered as a reasonable alternative for many experimental studies in vogue. They support best e.g. case studies made over longer observation periods.
2.1 The Auroral Turbulence II rocket experiment

One primary goal of rocket-borne in situ experiments in the Earth’s upper atmosphere is to study correlations between particles and magnetic and electric fields in auroral structures (Lühr, 1992; Primdahl et al., 1979). Numerous rocket investigations of auroral arc electrodynamics were performed during the last three decades (e.g. Evans et al., 1977; Marklund et al., 1982; Marklund, 1984). In a majority of these investigations, single payloads were used with very limited possibilities for distinguishing between spatial and temporal variations. Johnstone and Davies (1974) reported two-point measurements of breakup aurora using a mother-daughter payload combination.

The present study utilizes measurements of the first successful three-payload auroral rocket experiment. The Auroral Turbulence II sounding rocket was launched from the Poker Flat Research Range near Fairbanks, Alaska, USA at 8:36 UT on February 11th, 1997, under no-moonlight conditions. It carried three payloads, Baby, Daughter and Mother, into the upper atmosphere, with an apogee of 500 km. The flight lasted for about 1200 seconds and several distinct auroral arc structures were crossed. These are investigated in this study. The purpose of the mission was a comprehensive investigation of variations, in space and time, of plasma properties within and around an auroral arc. In particular, the relation between the electric field and plasma flow velocities, and the particle precipitation and magnetic perturbation, could be addressed over a wide range of scale lengths. Ground-based observations were available and observations by the Polar satellite were used to obtain a general picture of the auroral event.

2.2 Rocket instrumentation

The Baby and Daughter payloads were each ejected from the Mother ("Main") payload at about 10 m s\(^{-1}\) separation speed and at an angle of 45 degrees with respect to the B-field (Figure 2.1). Thus, a triangle of observation points was provided, the sides of the triangle expanding during the flight from 0 to 6 km, both perpendicular and parallel to the B-field. Each payload was equipped with a vector electric field instrument (Cornell College, University of New Hampshire (UNH), Dartmouth College) ion and electron mass-spectrometers (UNH) and a 3-component fluxgate magnetometer with resolution of 0.11 nT bit\(^{-1}\) for Daughter and Baby, and 0.15 nT bit\(^{-1}\) for mother (Primdahl et al., 1994). The magnetometer provided measurements of the B-field with a sampling rate of 2.0 kHz.
Figure 2.1: The three payloads of the Auroral Turbulence II (AT-2) rocket experiment are sketched in formation as they were crossing a large auroral arc. This arc orientation is found in all sky camera data as well as from e.g. magnetic data studies (Chapter 2.5).

The Mother payload carried in addition several other instruments: two different wave-particle correlators and the Plasma Frequency Tracker, both for measurements of waves and particles near the plasma and upper hybrid wave frequency. The electric field probes allowed high frequency sampling up to 6 MHz. The UNH burst computer was programmed to enable fast detection of changes in the particle precipitation pattern. The ambient electron density was measured by the Plasma Frequency Probe (Dartmouth). The magnetometer was a new type of digital fluxgate instrument (Primdahl et al., 1994), where the normal analog electronics were replaced by algorithms implemented in a Digital Signal Processor.

2.3 Geophysical background of the rocket experiment

The geomagnetic background at the time of the AT-2 sounding rocket experiment was measured by a network of satellite and ground-based instruments.
Figure 2.2: All measurements in the above figure were made between 00:00 to 12:00 UT on February 11<sup>th</sup>, 1997. Top: IMF B<sub>z</sub> component measured by the Wind satellite, depicting a southward turning at about 04:30 UT responsible for the start of substorm development. Middle: GOES-9 B<sub>z</sub> component starts to decrease at about 05:15 UT indicating the start of substorm growth phase. Bottom: The magnetic H-component at Poker Flat Observatory, depicting substorm onsets at about 08:13 UT and 09:45 UT.
The day of the rocket experiment (February 11th, 1997) was characterized by disturbed geomagnetic conditions (daily $Ap=211.15$). The interplanetary magnetic field and solar wind parameters were measured by the Wind satellite which was located between Earth and Sun at about 200 $Re$ from the Earth. The magnetic field $B_z$ component (Figure 2.2 upper panel, GSM coordinates) was small and positive (about 5 nT) before 04:30 UT. At that moment, a sudden turn of the magnetic field $B_z$ component to -5 nT occurred. The solar wind velocity was about 450 km s$^{-1}$ and the $B_z$ disturbance reached the Earth’s magnetosphere at about 05:15 UT at the time delay of about of 45 minutes.

The Geosynchronous Operational Environmental Satellites (GOES) operate on a geostationary orbit at about 6.6 Earth radii close to the Earth’s equatorial plane. GOES 9 is located at about 227° East, close to the field line of Poker Flat. In Figure 2.2 (middle panel), the $B_z$ magnetic component (GSM coordinates) measured by GOES 9 is shown. After 05:00 UT, the magnetic field begins to decrease. This indicates tailwards stretching of field lines.

After 05:00 UT, at the same time as the magnetic field began to decrease at the GOES 9 orbit, the meridian scanning photometer at Poker Flat (Figure 2.5) observed an increased precipitation. The Poker Flat magnetic H-component increased, too (Figure 2.2 lowest panel).

The rocket observations occurred in disturbed geomagnetic conditions. The geophysical background of the substorm is described in detail in Danielides et al. (1999). At about 08:13 UT, a sharp decrease of about 700 nT in the magnetic H-component occurred at Poker Flat, indicating a substorm onset (Figure 2.3). The auroral break-up occurred in the vicinity of the launch region. It was seen in a sequence of ultraviolet images obtained from the Polar Satellite (three frames are presented in Figure 2.4).

### 2.4 Optical observations during the rocket mission

At 08:36 UT, 23 minutes after the substorm onset, the AT-2 sounding rocket was launched into the westward travelling surge (WTS) wake environment. Two global UV images taken at 08:38 and 08:47 UT (Figure 2.4b and c) demonstrate the auroral background during the experiment, characterized by a gradual decrease of the auroral activity. The circle near 21 MLT indicates the field of view of the all-sky camera in Fort Yukon (FY), which corresponds to the region of observations reported here.
Figure 2.3: Magnetic X-component at Poker Flat, Alaska on February 11\textsuperscript{th}, 1997 from 07:00 to 09:00 UT. The times a, b, c indicate the times of Polar Satellite coverage (Figure 2.4). The time interval 08:40 to 08:42 UT addressed in this study is marked by two vertical lines.
Figure 2.4: Rendered projection of the Polar Satellite ultraviolet imager data for a) 08:14 UT, b) 08:38 UT as well as c) 08:47 UT on 11th February, 1997 on the northern polar cap. The coastline of Alaska is shown in the lower left quadrant. A westward travelling surge wake is found close to the northern coast of Alaska. The AT-2 rocket experiment was launched into this region towards the north. The field of view for the Fort Yukon TV all-sky camera (FY-TV) in Alaska is marked.
Figure 2.5: A meridian scanning photometer located at the rocket launch facility Poker Flat monitored the auroral activity of the night February 11th 1997. It is seen that before 07 UT an intensive auroral structure occurred. From 07 UT until 12 UT a sequence of auroral substorm onsets are seen. The rocket was launched into this sequence of substorms close to local midnight after an onset at 08:20 UT. The intensities decreased right after the launch at 8:36 UT.

The UV-imager (Torr et al., 1995) on the Polar satellite was used for the optical coverage from space. Its data provides a large-scale view of auroras compared to ground-based optical observations.

In addition to the Polar satellite ground-based optical observations were made at three places in Alaska, at Poker Flat, Fort Yukon and Barter Island - Kaktovik by all-sky cameras and meridian scanning photometer (Figure 2.5) were used.

At about 8:42 UT (after 330 seconds of the rocket flight) the payload cluster crossed a moderately active arc. The magnetic field measurements on the three payloads were found to correlate very well with the optical emissions measured on ground (to be shown later). The position of the rocket payloads was determined by radar measurements and the altitude of auroral arc was estimated by triangulation.

Before the time of crossing the above mentioned moderately active arc, the payload cluster was crossing patch-like auroral structures while frequently observed, they have only seldom been investigated by in-situ and ground-based optical measurements.
2.5 Rocket magnetic field measurement

Magnetometer data analysis involves the instrument calibration and transformation from a coordinate system moving and rotating with the rocket to physically meaningful coordinates. A precision calibration of the magnetometer was carried out before the launch. However, DC offsets and scale factors changed during the flight. This resulted in a spin modulation of the total magnetic field, when the preflight calibration values were used. Thus in-flight calibration procedures were necessary to determine the exact scale factors and to remove drifts. This was done using linear regression which minimizes the difference between the square of the measured total magnetic field from the square of the modeled magnetic field. The modulation due to rocket rotation can be reduced significantly with residuals of ~3 nT rms after calibration. The sounding rocket motion on the part of trajectory of scientific interest is essentially a free-body rotation with angular momentum conserved. Due to the axial symmetry of the rocket, the rotational motion can be described as a combination of spinning around the symmetry axis and precession (coning) of the spin axis around the angular-momentum direction in the same sense but at a lower rate.

Figure 2.6 presents deflections of the measured magnetic field by two of the three payloads (Baby/North and Daughter/East) from the International Geomagnetic Reference Field (IGRF) model (Peddie, 1982). The measured magnetic field was scaled so that the minima in the model field and the measurements were the same. This provided a good correspondence of the measured data with the model. The upper panel presents the variation of the total magnetic field value (longitudinal deflection). Two panels in the middle present the transverse variations observed on two payloads. The lowest panel shows the of field-aligned currents derived from the measurements presented in the first three panels. All the data presented are sliding averages using a window of 6 seconds. On this large scale (equal to 6 km of payload motion), all three payloads should have observed the same features. Only the best-resolved components in the magnetic field-angular momentum plane are shown in Figure 2.6. In the following, the orientation of the auroral arc structure at about 8:42 UT (between 300 to 400 seconds in the rocket flight) is studied. Homogeneity along the arc in the magnetic east-west direction is assumed. The arc deflection from the geographic East is derived from the FACs inside the arc (Figure 2.6)):

$$\tan \alpha = \frac{\delta B_N}{\delta x},$$

(2.1)

With $\alpha$ equal about 40 to 45 degrees from the geographic East, a gen-
Figure 2.6: a) The total magnetic field value measured by the AT-2 payload cluster minus the International Geomagnetic Reference Field model. The Auroral Turbulence II magnetic field measurements in the magnetic vector and rocket momentum vector (B,L) plane are shown for b) the north-south component (Baby) and for c) the east-west component (Daughter). The variations of field-aligned currents measured by Baby and Daughter payloads are shown in d).
Figure 2.7: Geographic map of Alaska, showing the Poker Flat and Fort Yukon stations. The AT-2 rocket trajectory as well as the field of view for the Fort Yukon ASC station are shown. The position of the AT-2 payloads is marked (diamond) for 11\textsuperscript{th} February 1997 at 08:41:00 UT. The auroral structures under investigation are plotted as a geographic projection. Arcs are numbered from 1 to 3 as discussed in the text.

Several correspondence to the optical observations is found. The difference of about 10 degrees between optical and magnetic observations was discussed in Danielides et al. (1999). It was possibly caused by inhomogeneities inside the arc. For the upward field-aligned current, a value of 0.17 A m\(^{-1}\) was found. The downward field-aligned current equatorwards of the arc is \(\sim 0.05\) A m\(^{-1}\), and the field-aligned current polewards of the arc is 0.12 A m\(^{-1}\).

In Paper I and, e.g., in the paper by Ivchenko et al. (1999), only the most intense large-scale auroral signatures were studied which the payloads crossed after 08:42 UT. These are related to the most poleward arc 3; see Figure 2.7. The main aim of Paper IV is to focus on the arc 2 and associated auroral fine structures, which were crossed at around 08:40 to 08:42 UT.

It is important to note that the arc was not homogeneous along its length:
bright patches inside arc 2 (indicated by letters a, b, and c; see Chapter 3.4) were propagating westward along the arc, so that patches a and b passed close to the payload position at about 08:40:35 UT and 08:41:10 UT, respectively. The spatial size of the patches was of the order of 100 km. In the course of the observations, the arcs decayed by developing into the auroral patches and arc segments in a diffuse background.

The observed auroral arcs before 08:42 UT (Figure 2.7) are typical discrete auroral structures developing within the bulge expanding poleward during a substorm, as was described by Nakamura et al. (1993) (p. 5743): "At the eastern part of the bulge, thin auroral features propagate eastward from the breakup region. Around the central meridian of the bulge, auroral features expand equatorward and become north-south aligned (the N-S aura). The N-S aura and the eastward-propagating aura develop into diffuse and pulsating aura after the expansion." In Figures 2.7 and 3.1, the most poleward intensive arc 3 corresponds to the aurora propagating eastward. This arc studied in earlier papers was quite stable, whereas arc 1 can be identified as a "N-S" aurora decaying at the substorm recovery by developing into diffuse and pulsating aura. Arc 2 is oriented in a NW-SE direction.

Paper IV presents a detailed investigation of the electric field and auroral fine structures associated with arc 2 (Figure 2.7), which was crossed by the payload at around 08:40 to 08:42 UT, during the substorm recovery.

2.6 Imaging riometer technique

The riometer method is based on the detection of penetrating cosmic noise signals in the radio frequency range to monitor absorption processes in the upper atmosphere. The imaging technique uses an array of multiple, narrow antenna beams pointing in different directions. A 2-dimensional sky map (image) of absorption intensity may be derived from the observed cosmic noise signal intensities.

Radio-wave absorption appears as the consequence of collisions between electrons and ions, neutral atoms and molecules. The electrons are accelerated by the wave and this energy is transferred to the heavier particles through collisions. The loss rate of the radio wave energy (the absorption intensity) depends on the density of electrons and on the frequency of collisions. Investigations of radio-wave absorption phenomena may thus provide information on ionization, electron temperature, and the collision frequencies.

With a state-of-the-art imaging riometer (IRIS) at Kilpisjärvi, Finland, these fundamental upper-atmosphere parameters are recorded on a contin-
Figure 2.8: The projection onto the ionosphere at 90 km altitude of the Kilpisjärvi IRIS imaging riometer beams.

uous basis. The imaging riometer data used in the present studies (Papers III and IV) were obtained from the Kilpisjärvi IRIS system in northern Finland (69.05 N, 20.79 E, L≈ 6). The system operates at 38.2 MHz and uses an array of 64 crossed half-wave dipoles over a ground plane, with a set of Butler matrices from 49 independent beams. The signals are received by time-sharing into 7 riometers, the outputs of which are digitized (12 bits) every second. The zenith beam is 13 degrees wide between half-power points and the best spatial resolution at the altitude of 90 km is 20 km.

The single absorption signals are either integrated to obtain total absorption or are presented on a geographic grid (Figure 2.8). The second option allows identification of the absorption pattern in the field of view. Observations with an imaging riometer, with its multiple narrow beams and superior spatial resolution, allows us to produce two-dimensional "images" of the patches of enhanced CNA as they evolve over time. Thus, observations can be made of the spatial scale, morphology and dynamics of MIE-associated absorption patches. This enables further refinement of the characterization of MIEs by distinguishing events of comparable magnetic signatures such as FTE, precipitation spike events (Stauning and Rosenberg, 1996), and Travelling Convection Vortices (TCV’s) (Glassmeier, 1992).
Chapter 3

Methods of data analysis

This chapter presents the analysis of the multi-instrumental data based on the methods described in the previous chapter. The AT-2 rocket experiment included both in-situ and ground-based observations. The ground-based observations were mainly optical measurements, whereas the rocket-based in-situ measurements to be discussed in this study were electric and magnetic field measurements.

Estimations of FAC densities have been performed purely from ground-based magnetic and riometer observations. A general background on the estimation of FACs is given, followed by a brief section on the FAC density threshold. Finally, the actual method on estimating FAC densities in current-carrying filaments is described.

3.1 Optical data analysis in the framework of rocket observation

The AT-2 rocket experiment (Chapter 2.1) was accompanied by optical instrumentation. Using this multi-instrumental optical setup, a general case study was done by Danielides et al. (1999). There, the rocket trajectory was projected onto the ASC frames (Figure 3.2).

The altitude of the auroral display of about 95 - 105 km was obtained by triangulation. Initial observations made by the Polar Satellite UVI (Figure 3.3) give an overview on the larger auroral structures (fraction of the northern auroral oval) over Alaska at the time of the AT-2 rocket experiment. They are mapped onto a geographic grid. The rocket trajectory is also plotted in Figure 3.3.

A global view of the northern polar cap was presented in Figure 2.4 using Polar UVI observations. A westward-traveling surge wake is found close to
Figure 3.1: The nine all-sky video frames show the auroral situation from 08:40:15 to 08:41:40 UT on 11th February, 1997 at the Fort Yukon station. Geomagnetic North is up, geomagnetic East on the right and the centre of each frame is marked with a small cross. In the Northwest, the rocket position is shown as red points. The in-situ electric field (green line) is added to each frame. The auroral situation is active and luminous auroral structures a, b and c are marked.
Figure 3.2: All-sky images taken on February 1\textsuperscript{st}, 1997 at 08:41:05 (a,c,e) and at 08:42:00 (b,d,f) LT at Poker Flat, Fort Yukon and Barter Island - Kaktovik.
Figure 3.3: Auroral structures above Alaska, taken by Polar satellite UV-Imager on February 11th, 1997 at 08:41:05 and at 08:42:00 LT. Poker Flat and the rocket trajectory are marked.
the northern coast of Alaska. The localized field of view of the TV all-sky camera at Fort Yukon (FY-TV) was marked there by a circle.

Paper I mainly focuses on a large quiet auroral arc structure (Chapter 3.2), whereas Paper IV investigates auroral patches in the vicinity of this quiet auroral arc. This unique opportunity to study auroral patch-like structures with a multi-instrumental setup required a special approach.

The regions of luminosity are indicated on ASC frames (e.g. Figure 3 of Paper IV). For the selected auroral structures, 20 points connected by a line cover the lower edge of the arc-like structures. An arrow indicates rocket payload position in each ASC frame. It is assumed that the lower edge of the auroral luminosity is at ~105 km, which is the estimated altitude of the patch-like structures. The selected arc-like structures are plotted onto a geographic map (Figure 2.7). The rocket trajectory (blue line pointing northward from Poker Flat) and payload position (diamond symbol on top the trajectory) are added.

As the next step, nine all-sky video frames from Fort Yukon (Figure 3.1) show the auroral situation along the rocket trajectory at 08:40 to 08:42 UT. In the western part of each frame, the rocket position (mapped along the magnetic field line to 105 km altitude) is shown together with its local geographical coordinate system, and vectors in the rocket location present the in-situ measured electric field. Thus, Figure 3.1 shows the rocket position when crossing arc 2.

For a more detailed consideration, the auroral structures associated with arc 2 were plotted onto a geographic map. Sketches in Figure 3.4 show a sequence of the aurora positions in the rectangular coordinate frame having its origin at Fort Yukon and vertical axis pointing to the geomagnetic pole. The main interest is focused on the locations of arc 2 and the bright spots (patches a, b, and c) moving along this arc. Locations of auroras are represented by the position of their lower edges, which is the sharp edge most distant from the zenith in the TV frames. The locations of the lower edges were determined several times manually for each frame; this allowed us to find the average values and estimate the errors, which were of the order of 20 km. Those "error bars" create the strip-like sketch of the auroral arc in Figure 3.4. The arc was oriented from northwest to southeast at an angle of about 20 degrees from the geomagnetic latitude. The most intense luminosity regions of patches a and b are marked by asterisks with corresponding letters. The patches propagated to the west at a velocity of about 3 km s\(^{-1}\) following each other at a distance of the order of 200 km along the arc. At the interval between patches b and c, the auroral arc forms a fold-like structure bowed northward.
3.2 Analysis of electric field and current signatures measured during the rocket experiment

As already explained in Section 3.1, there were separate studies on the quiet and active auroral forms during the AT-2 rocket experiment.

At first, a quiet arc with its FAC and electric signatures was studied (Paper I and Danielides et al., 1999). The initial step was to run an inflight calibration (Prindahl et al., 1984) and to transform the measurements to a non-rotating coordinate system (Section 2.5). The raw electric field
Figure 3.5: Plasma drift velocity calculated from in-situ electric field measurements, here presented as plasma flow (panel a), split into components: b), plasma flows across the arc (Vx) and c), plasma flows along the arc (Vy). The plasma drift velocity components are given in an arc-associated coordinate system (horizontal line; about 20 degrees offset from the geomagnetic coordinate system). The auroral patches marked in Figures 3.1 and 3.4 are marked as a, b and c.

data were despun using a rigid-body motion model derived from the onboard magnetometer data.

Based on the previous analysis of the electric-field vectors, a study of the active optical auroral signatures during the AT-2 rocket experiment was performed in Paper IV.

The location of the rocket is marked on the grid in Figure 3.4 as a dot with a vector, where the vector represents the plasma drift velocity, $\vec{v} = (\vec{E} \times \vec{B}) / |B|^2$, calculated from the in-situ electric field measurement. The plasma drift velocity vectors of Figure 3.4 are presented in an arc-associated coordinate system in Figure 3.5a. The plasma drift velocity vectors form a vortex structure with its focus westward of the auroral patch denoted as b. This vortex structure is due to both the occurrence of an auroral arc associated electric field and an auroral patch associated electric field. One can separate
the plasma velocity vectors into 2 components corresponding to the plasma flows along the arc \(V_y\) and across the arc \(V_x\) in the arc-associated coordinate system. The auroral patch indicated as b is taken as a local reference point within the auroral arc structure. Then the auroral patches indicated as a and c are shown at their mean distance to b. Spatial variations in the cross-arc plasma flow \(V_x\) can be attributed to the inhomogeneous structures distributed along the arc. Also, we have presented \(V_x\) in the framework of the moving patches (Figure 3.5b). This plot demonstrates that the auroral patches were associated with equatorward plasma flow (across the arc) of the order of 200 m s\(^{-1}\), whereas in the intervals between the patches, the cross-arc plasma flow is greatly reduced and tends to be poleward.

Figure 3.5c shows the plasma velocity component along the arc \(V_y\) versus the distance from the northern edge of the arc. This plot demonstrates that the arc was associated with a westward ionospheric plasma flow of the order of 300 m s\(^{-1}\), and convection reversal occurred at the northern edge of the arc. So, just poleward of the arc, the plasma flow was eastward at about 200 m s\(^{-1}\). Thus the arc corresponds to a Birkeland current type arc according to the classification by Marklund et al. (1984).

### 3.3 On the estimates of FAC

Traditionally, the intensity of auroral electrojets has been deduced from ground-based magnetograms. Negative excursions of the north component are interpreted as due to a westward current in the ionosphere, whereas positive bays are taken to imply eastward currents. Obviously the vertical currents were neglected in this type of analysis. It results in an equivalent current system rather than a true one - indeed, there is no way of deducing the vertical current component from purely ground-based magnetic observations.

The essential differences between vertical and horizontal current systems are shown in Figure 3.6. In (a), two Birkeland currents are connected by an electrojet. (a) is equivalent to (b) plus (c), where (c) demonstrates an electrojet that in principle could close entirely in the ionosphere. (b) may be divided into (b1) and (b2), each comprising a vertical current and a spreading current in the ionosphere. Neither (b1) or (b2) produce any magnetic effect beneath the ionosphere. Thus, for the ground-based observer (a) and (c) look the same. However, (b1) and (b2) do produce magnetic effects above the ionosphere. These effects were found after rockets and satellites were launched into Earth’s upper atmosphere.

Birkeland currents have been estimated based on ground-based observa-
tions since then. The estimates are compared with "space-truth" (meaning satellite or rocket in-situ measurements) if available.

Usually one has to distinguish between local and global methods. The global methods utilize larger networks of instrumentation (mostly magnetometers and various radars) in order to record a general picture of the electrodynamic features of the high-latitude ionosphere (Kamide et al., 1981; Richmond and Kamide, 1988). These methods are designed to derive electric potential patterns from which the ionospheric currents are calculated by using conductance models. Lately, methods of characteristics by Inhester et al. (1992) and Amm (1995) have been presented which can equally be applied on local and global scales. By using arrays of ground-based magnetometers (e.g., IMAGE network; Lühr et al., 1996) one may estimate FACs, but one has to know the full conductance distribution, which is generally not available. Using models of ionospheric conductances together with the measured electric field, the currents are inferred. Even if the full conductance distributions were available, the technique still suffers from an inherent low spatial resolution of $>120$ km.

There the primary output is the ionospheric conductances from which, together with known electric field measurements, the currents are inferred.

Estimates of spatially localized electron energies and number fluxes, from which one would be able to reconstruct also FAC densities, have been proposed (Janhunen, 2001). These estimates are mainly based on ground-based optical measurements. Obviously this method has its limitations due to local cloud coverage, and the all-sky imager operates only at certain selected wavelengths, while data from optical observations at several wavelengths are needed.

By using radars (e.g. CUTLASS, STARE or EISCAT) or riometers (wide-beam or imaging riometers), the measurements are independent of cloud coverage. Incoherent radars (e.g. EISCAT) can, at least in principle, directly measure FACs but no one has done this convincingly. This technique suffers in any case from low temporal resolution because of the need to scan the radar. Coherent radars (e.g. CUTLASS and STARE) can measure the ionospheric electric field distribution with high spatial and temporal resolution. However, they lack the ability to measure conductances. Computing FACs from electric field distributions is theoretically well established and requires knowledge of the Pedersen and Hall conductances as well as their spatial gradients. That information would be supplied by a calibrated multi-wavelength imager. This approach is highly weather dependent but it promises a high spatial and temporal resolution. However, the multi-wavelength imagers do not produce "good" data continuously.
3.4 FAC density threshold

In Paper III and references therein, it is emphasized that auroral activation on the nightside can be triggered if the FAC density exceeds a certain threshold. FAC density is measured in A m$^{-2}$, and the threshold value is of the order of \( \sim 10 \, \mu \text{A m}^{-2} \). Such an effect can be associated with magnetic fields. Those are, when seen at ground level, of the order of 50 - 100 nT (Paper IV; Kamide, 1993). However, the magnetic effect on the ground is not produced directly by FACs as explained later (Chapter 3.5).

Exceeding this threshold leads to activation of the accelerator region. This causes the development of anomalous resistivity (Papadopoulos, 1977) and dissipation in the current-carrying plasma whose evolution is manifested in the occurrence of additional precipitating (aurora), PiB pulsations and concurrent variations of riometer absorption as well as in patterns within imaging riometer observations and many others.

The spatially and temporally restricted energy release is observed during both the growth phase and at substorm onset.
3.5 A method to estimate FAC densities in current-carrying filaments

In this Section, a method (Paper III) is presented to estimate FAC densities from CNA pattern and ground-based magnetic signatures. It is based on a theoretical study by Pilipenko et al. (1999) (see also Paper IV). Utilizing only ground-based magnetometer and imaging riometer data, this method is localized (spatial resolution ~100 km and temporal resolution down to 1-10 seconds) and continuously available, e.g. during an MIEs event.

This method assumes that electrons transporting the field-aligned current and energetic electrons producing an additional ionization of the ionosphere are collocated within the same flux tube.

Lanzerotti et al. (1986) modeled the MIEs current system as a circular tube filled with homogeneous upward currents, whereas reverse currents flow along the tube’s surface. Following this theoretical approach, one may estimate the expected magnitude of the FACs above the ionosphere, which produce magnetic impulses. It is known that the localized structure of magnetic impulses indicates that these disturbances are transported from the distant magnetosphere to the ionosphere via Alfvén waves (Frank et al., 1997). The Hall current is an indicator of these magnetic disturbances in the ionosphere. While one cannot measure FAC directly from the ground (Section 3.3), it is possible to detect magnetic variations at ground level from which one reconstructs equivalent current systems. The total FAC, $I_0$, is related to the $b_z$ magnetic component. This can be expressed in the following formula (Lanzerotti et al., 1986):

$$ b_z = \frac{\mu_0}{8\pi} \frac{\sigma_H}{\sigma_P} \frac{a^2 I_0}{h^3}, $$

(3.1)

where $a$ is the dimension of the flux tube in the ionosphere, $h$ is the height of the ionospheric layer, $\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$ is the magnetic permeability and $\sigma_H, \sigma_P$ are the height-integrated Hall and Pedersen conductivities, respectively.

Pilipenko et al. (1999) inferred from Eq. 3.1, using at that time typical observed values ($b_z \approx 100$ nT, $a = h = 100$ km and $\sigma_H/\sigma_P = 2$) that $I_0 \approx 10^5$ A. Hence, the density $j_{||}^{(i)}$ of the FAC tube above the ionosphere is of the order of $j_{||}^{(i)} = I_0 / a^2 \approx 10 \, \mu$A m$^{-2}$.

Also, the magnitude of FACs in the upper ionosphere producing auroras must be estimated. Swift (1978) noted that current-driven anomalous resistivity is associated with plasma turbulence where the electron drift velocity $V_D = j_||/ne$ is maximal. However, the height where this occurs must
be known. Mozer et al. (1980) used measured plasma profiles to determine that the drift velocity peaks in the region around 6000-7000 km. The current density $j_{\parallel}$ scales as the magnetic field strength $B$ when the current in a flux tube is conserved. The corresponding FAC density at this distance ($\sim 1 R_E$ about ground) was estimated (Mozer et al., 1980) to be

$$j_{\parallel}^{(m)} = 1.3 \cdot 10^{-6} \frac{A}{m^2}. \quad (3.2)$$

For a dipolar geomagnetic field $B(r) = B_E \cdot (R_E/r)^3$ (where $B_E$ is the magnetic field on the ground, at $r = R_E$), and using the conservation of magnetic flux and total current in a magnetic flux tube, the relationship between the FAC density $j_{\parallel}^{(m)}$ in the magnetosphere at a distance $R_m$ and $j_{\parallel}^{(i)}$ in the ionosphere at $R_i$ can be obtained as follows: $j_{\parallel}^{(m)} = j_{\parallel}^{(i)} \cdot (R_i/R_m)^3$. Assuming that $R_i \sim R_E$ and $R_m \sim 2R_E$, we obtain that the ionospheric FAC density is $j_{\parallel}^{(i)} \geq 10 \mu A \ m^{-2}$.

To plot a representative figure, we use the formula given in the Appendix of Paper III

$$j_{\parallel}^{(i)} = \left( \frac{2\Psi_0}{\mu_0 R} \right) \left( \frac{a(2a^2 - r^2)}{(a^2 + r^2)^{5/2}} \right) \quad (3.3)$$

for the FACs associated with observed magnetic disturbances and absorption spikes. Here, $R = \Sigma_H/\Sigma_P$ is the Hall to Pedersen conductance ratio and $\Psi_0$ is a ground magnetic amplitude factor.

Because fine details of the current structure are not significant for integrated magnetic effects on the ground, Pilipenko et al. (1999), following Glassmeier and Heppner (1992), chose the distribution of upward and downward currents to be described by a known magnetic potential $\Psi$. To this end we have to know the ratio $R$, the flux tube radius $a$, and the distance $r$ of the station from the center of a current-carrying filament.

Walker and Bhatnagar (1989) have estimated the Hall and Pedersen conductances from riometer data with the following empirical relations:

$$\Sigma_H = 1.49 + 16.7 \cdot A + 0.15 \cdot A^2, \quad (3.4)$$
$$\Sigma_P = 0.60 + 4.57 \cdot A + 0.07 \cdot A^2, \quad (3.5)$$

where $A$ is the ionospheric absorption in decibels [dB]. This absorption refers to a single-frequency riometer at 30 MHz. The IRIS Kilpisjärvi system operates at a frequency $f = 38.2$ MHz. Using a power law of the form

$$A(f_e) = C f_e^{-n}, \quad (3.6)$$
which was found by Lefald et al. (1964) from multi-frequency observations, it is now possible to relate other single-frequency riometer observations to 30 MHz observations. In Eq. (3.6), C is a constant and $f_e$ the effective frequency given by $f_1 \pm f_L$. Here $f_1$ is the (riometer) wave frequency. The electron gyrofrequency, $f_L$, is about 1.6 MHz at 90 km altitude, and the plus/minus corresponds to the ordinary/extraordinary wave mode. They found that $n$ can vary from ~1.0 for hard energetic events to ~2.0 for soft events. In practice, $n = 2$ is mostly used. Thus from Eq. (3.6) an absorption, $A(f)$, at another frequency $f_2$ will be given by

$$A(f_2) \approx A(f_1) \left( \frac{f_{e1}}{f_{e2}} \right)^n.$$  

From these formulas we can estimate the ratio $R$ for absorption observed with the IRIS system.

Figure 3.7 sketches the setup required for the present method to estimate FAC densities from CNA patterns. At the ground level, a multi-instrumental setup is required, consisting of an imaging riometer (e.g. IRIS Kilpisjärvi), a magnetometer as well as a pulsation magnetometer. Optionally, one may utilize optical instrumentation, e.g., an all-sky camera or multichannel photometer to investigate from the optical signatures the energy of the precipitation particles in addition to the structure of the observed aurora. In the case of satellite conjunctions above the IRIS field of view (Danielides et al., 2003), one can employ space-borne instrumentation as an additional input. However this is not required for the method outlined here. The imaging riometer detects CNA patterns from ionospheric altitudes and those are mapped usually on a geographic grid at 90 km altitude.

Recent studies (Terkildsen et al., 2004) have shown a strong peak of absorption occurring at the altitude range around 87-90 km and a significant number of events that peaked at higher altitudes, above 90 km.

A key requirement is that the FAC flux tube is co-located with the CNA pattern mapped to ionospheric altitude. The radii/distances $a$ and $r$ can be calculated by an algorithm as follows:

1. A background level for the absorption as the average value during the time interval under consideration (around 0.5 dB in our case) is determined.

2. For each absorption event above this level, the geographic coordinates of maximum absorption are determined. They are taken as the center of the current-carrying flux tube (hence a radius/distance $r$ from the observational point to the center of the tube is estimated);
3. The radius of the flux tube is simply taken as the half-width of the absorption patch image in the IRIS field of view.

The geometry, size and location of the absorption filament are used to estimate $j_\parallel$ from formula 6 in the Appendix of Paper III.

Taking all these points into account, the current density during the selected time interval was calculated and the result is presented in Figure 3.8 (lower panel). The dashed line marks a threshold value as estimated in the previous section. The threshold value ($10 \mu A \text{ m}^{-2}$) is exceeded by a factor of up to 4 or 5 during certain periods, when peak values of optical emission (auroral activity) were observed (Figure 3.8, upper panel).
Figure 3.7: The setup required to estimate FAC densities from ground-based signatures. Magnetometers, pulsation magnetometers as well as imaging riometer are located on the ground. These detect signatures from ionospheric altitudes and above, e.g. CNA patterns (red/dark oval at ionospheric height). This pattern has a radius and its center is located at a distance $R_{\text{dist}}$ (called $r$ previously in the text) from the vertically mapped location of the ground based-station. The FAC flux tube is sketched above. Possible satellite conjunction for in-situ verification is represented at higher altitudes.
Figure 3.8: The upper panel shows the normalized emission intensity from the ASC at Kilpisjärvi / Finland on 25th October, 1999, from 16:30 to 17:30 UT with 20 seconds resolution. In the lower panel, the field-aligned current (FAC) density as estimated by formula 3.3 is shown. A dash-dotted line shows the theoretically-estimated threshold value of 10 µA m⁻². The four major activations (i) at 16:42 UT, (ii and iii) around 17:10 UT and (iv) at 17:17 UT) clearly reach this value, whereas the last activation around 17:19 UT barely attains this threshold.
Chapter 4

Summary of the main results

The main results of this thesis can be summarized as follows:

4.1 Experimental results

A quiet auroral arc was the initial interest of the Auroral Turbulence II rocket experiment. The large-scale physics of the observed auroral arc was studied against its geomagnetic background. The auroral arc location was mapped and its field-aligned currents were determined from rocket in-situ measurements. The result goes along with the very consistent picture of upward FACs inside the arc structures and downward FACs in regions void of optical emission.

The electric field and corresponding particle in-situ measurements exhibited a region of highly localized, sheared, and intense DC electric field with a peak magnitude of at least 400 mV m$^{-1}$ at an altitude of 540 km. According to the particle measurements, this region was located near the poleward edge of the quiet auroral arc under study.

During the same rocket experiment, active auroral forms were observed. One of our interests was to investigate auroral patch-like structures and auroral arc segments. They propagated westward along the discrete arc structure. A detailed investigation of the electric field and fine auroral structures associated with these arcs was carried out.

It was found that the discrete auroral arc had a width of about 40 km and was stretched in southeast direction. The ionospheric plasma velocity along the arc was found to be 300 m s$^{-1}$ westward and convection reversal occurred at the northern edge of the auroral arc.

Auroral patches and associated electric fields formed a 200 km spatial structure. They propagated along the arc westward with a velocity of 3 km s$^{-1}$. 
These bright patches were co-located with equatorward plasma flow across the arc of the order of 200 m s\(^{-1}\) in magnitude, whereas in the intervals between the patches, the plasma flow tended to be poleward.

In the patches, the electric field reached at most magnitudes of up to 20 mV m\(^{-1}\), and these maxima were co-located with the peaks in electron precipitation as indicated by the electron counter on board the rocket experiment.

Pulsations of 70-seconds period in the eastern component of the magnetic field were observed on the ground, which is consistent with the velocity, spatial size, and convection pattern of the moving auroral patches.

### 4.2 Derived parameters

Surpassing a threshold value of the FAC density coincided with a substorm intensification. The FAC value is estimated in the present study. Auroral activations on the nightside associated with MIEs produced spatially and temporally restricted energy releases during both the growth phase and substorm onset with the following characteristics: i) The low magnetic activation (about 50 - 100 nT) is regulated by the upward FAC density (about 10 \(\mu\) A m\(^{-2}\) at ionospheric altitudes) and is required to activate the accelerator at about 1 \(R_E\) altitude. ii) This leads in turn to anomalous resistivity and dissipation in current-carrying plasma, which manifests in aurora, Pi1B pulsation and concurrent variations of riometer absorption. This explains the correlation of auroral and Pi1 pulsations in conjunction with FACs.

The method proposed to estimate FAC densities from riometer and magnetic measurements seems to be applicable. In cases of no large temporal delay (exceeding a few seconds) between auroral and absorption events, the estimated FAC intensity may be associated with localized auroral structures. These have to be within the field of view of both IRIS and ASC.

### 4.3 Interpretation

It is proposed (Paper IV) that the observed evening auroral patches are due to the magnetospheric surface-type wave propagation along the boundary of the plasmasheet.

The physics of the other aspects (Papers II and III) of the present studies is suggested:

Some part of the current is attributed to high-energy particles (10 - 20 keV) that are responsible for the absorption spikes. ii) The other part
Figure 4.1: Left Figure: Geographical map of northern Scandinavia. An imaging riometer plot from IRIS at Kilpisjärvi / Finland at 17:08 UT on January 31st, 2001 with a DMSP 12 satellite conjunction. The times of conjunctions with their geomagnetic footprints are marked in the figures. Right figure: A comparison between the actual in-situ FAC densities (blue line) computed from the magnetic measurements from the DMSP 12 satellite, and estimates of FAC densities (red spots). The times correspond to those from the left figure. Time periods of DMSP satellite crossings (geomagnetically) of the IRIS field of view are marked with red dashed lines.

of the current is attributed to relatively cold plasma (< 1 keV). This leads to a well-developed region of anomalous resistivity (Papadopoulos, 1977). It is followed by the development of both aurora and PiB pulsation.

The FAC is assumed as a connection between auroral activation and magnetic impulse events, as it connects the auroral ionosphere (Chapter 1.5) and the plasmasheet. The magnitude of energy release during each activation creates excitations of low-frequency turbulence in the upper ionosphere. This results in a quasi-oscillation regime of previously mentioned anomalous resistivity along the auroral field lines and rises to burst-like (pulsed) electron acceleration, as well. The anomalous resistivity and dissipation in the current-carrying plasma are responsible for simultaneously observed auroral forms, bursts of PiB pulsations as well as concurrent variations of riometer absorption.

4.4 Perspectives

In Figure 4.1, estimates of FAC densities are plotted together with "space truth" values derived from the DMSP 12 satellite. The satellite was crossing
an absorption filament at about 17:08:30 UT. Satellite conjunctions above IRIS systems during MIEs and PiB pulsations are very rare. Taking the lower resolution of IRIS (in this case 10 seconds resolution) into account, the result is surprisingly good. In most cases, the time intervals when the estimated FAC density exceeded the theoretical threshold for the ion-acoustic plasma instability coincided with intensifications of the auroral emission.

A calibration procedure has still to be found for the FAC density. A statistical study of events including, e.g., EISCAT radar, satellite or rocket in-situ measurements is proposed for this purpose.

In this thesis, the estimate of FAC density from ground-based riometer and magnetic measurements was carried out from a limited field of view. Only one imaging riometer was used. Already today a global riometer and IRIS network is under development. As a result, it would be possible to estimate FAC densities everywhere by GloRiA (GLObal RIometer Array) without the necessity to wait for e.g. satellite conjunctions.
Chapter 5

Appendix

5.1 Notation

\begin{itemize}
  \item \( A \): cosmic noise absorption
  \item \( A_p \): \( A_p \)-index
  \item \( a, \) Radius: FAC flux tube (Figure 3.7)
  \item \( \mathbf{B}, \vec{B} \): magnetic field
  \item \( B_e \): magnetic field at ground level
  \item \( b_z \): vertical magnetic component
  \item \( d, \) \( R_{dist} \): distance from magnetometer station (Figure 3.7)
  \item \( \mathbf{E}, \vec{E} \): electric field
  \item \( E_e \): electron energy
  \item \( E_{\parallel} \): field aligned electric field
  \item \( e \): elementary electric charge
  \item \( f \): frequency
  \item \( f_e \): effective frequency
  \item \( f_L \): gyro frequency
  \item \( h \): height of ionospheric layer
  \item \( I_0 \): total FAC
  \item \( j_{\parallel}, j_{par} \): field aligned current density
  \item \( j_{(i)}, j_{(m)} \): ionospheric and magnetospheric field aligned density
  \item \( L \): L-shell parameter
  \item \( \mu_0 \): vacuum permeability
  \item \( \vec{L} \): rockets momentum vector
  \item \( N \): number density of charged particles
\end{itemize}
\(n\) particle (number) density
\(\nu\) collision frequency
\(r\) radius/distance
\(R\) ratio Hall to Pedersen conductance
\(R_i, R_m\) distance to ionosphere / magnetosphere
\(\Sigma_H, \Sigma_P\) Hall and Pedersen conductance
\(\sigma_B\) effective Birkeland conductivity
\(\sigma_H, \sigma_P\) Hall and Pedersen conductivity
\(t\) time
\(V\) plasma drift velocity
\(V_x\) plasma flow across an arc
\(V_y\) plasma flow along an arc
\(V_D\) electron drift velocity
\(v_x\) solar wind velocity
\(v_y\) velocity along x component in Figure 1.4
\(v_{||}\) field aligned velocity component
\(\Psi\) altitude
\(\Psi_0\) ground magnetic amplitude factor (e.g. in eq. 3.3)
\(X, Y, Z\) Cartesian coordinates
\(x, y, z\) Cartesian coordinates; \(x\) is in eq. 1.1 a vertical distance
\(\omega\) angular wave frequency

5.2 Rocket instrumentation - technical overview

i) General description:

Black Brant XII 40.011 UE, Auroral Turbulence II, (Figure 5.1) was basically a replica of the 40.005 UE payload launched in March 1994. However, since 40.005 UE was not recovered, this was a newly-constructed payload. The Faraday Ring Ammeter system will not be reflown. The overall payload was comprised of three individual payloads: two subpayloads and a main payload. They have been designated as Baby, Daughter, and Mother. The Baby and the Daughter are separated from the Mother using an air spring deployment system. The Mother payload includes forward and after experiment sections, a three-link telemetry section, and a Space Vector attitude control system. Each of the payloads contains particle detectors and electric and magnetic field measurement instruments, including deployable E-field boom sets.
ii) Mother payload:

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Organization</th>
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</thead>
<tbody>
<tr>
<td>Fast Event Computer System and 1.024 Mbit/sec PCM link</td>
<td>UNH</td>
</tr>
<tr>
<td>Particle Detectors, Correlators and Electronics</td>
<td>UNH</td>
</tr>
<tr>
<td>Electric Field &quot;Minnesota-type&quot;</td>
<td>CU</td>
</tr>
<tr>
<td>Boom Sets and Electronics</td>
<td></td>
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<tr>
<td>Plasma Frequency Tracker Electronics and 5 MHz FM link</td>
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<tr>
<td>High-sensitivity Deployable Magnetometer</td>
<td>TUD</td>
</tr>
<tr>
<td>Digital ACS and Gyroscope</td>
<td>Space Vector</td>
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<tr>
<td>3-Axis Aspect Magnetometer</td>
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<tr>
<td>3.2 Mbit/sec Telemetry System</td>
<td>NASA</td>
</tr>
<tr>
<td>Separation Velocity Banner Scanner</td>
<td>NASA</td>
</tr>
<tr>
<td>C-band Radar Beacon/TRADAT/Support Electronics</td>
<td>NASA</td>
</tr>
<tr>
<td>TRADAT Ranging System</td>
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</tbody>
</table>
iii) **Baby / Daughter payloads:** (identical instruments)

<table>
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<th>Experiments</th>
<th>Organization</th>
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<td>3.2 Mbit/sec Telemetry System</td>
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<tr>
<td>Separation Velocity Banner Scanner (Daughter Only)</td>
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<td>Strobe Light</td>
<td>NASA</td>
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<tr>
<td>Supporting Electronics</td>
<td>NASA</td>
</tr>
</tbody>
</table>

iv) **Fluxgate magnetometer:**

Since the author was mainly involved with the analysis of magnetometer data, only the fluxgate magnetometer was sketched in some details, and other rocket experiments are not mentioned.

The principle of operation was the same as in a normal analog fluxgate magnetometer, which generates a nulling signal to the sensor to compensate the external field. The sensor was excited at 8 kHz and the signal was sampled by a 12 bit Analog to Digital Converter (ADC) with 16 times oversampling (128 kHz). The magnetic-field dependent part of the sensor signal is detected by cross correlating the input with a known reference signal. This was done twice in every excitation cycle, allowing detection of a theoretical maximum at frequency of 8 kHz.

The output from the correlator was fed into a digital integrator and fed back to the sensor through an 18-bit Audio Digital to Analog Converter (DAC). To enhance the resolution of the DAC to 20 bits, an Infinite Impulse Response filter algorithm was applied to the signal, giving frequency response equal to a 4th order Bessel filter with -3 dB frequency of 700 Hz. The output from the magnetometer is decimated to 2 kilowords s\(^{-1}\).

Two types of fluxgate sensors were used for the magnetometers. One type, designated Astrid, was used on the daughter and baby payloads,
while an older type (CSC, Compact Spherical Coil) was used on the mother payload. The Astrid sensor was a compact sensor, where the detector coil was also used as a compensation coil. The core material, made by TUD, was a metallic glass composition, and the inherent noise was below 20 pT rms (at 0.01-10 Hz). The CSC sensor uses an external coil for compensation, which results in a larger sensor. The core material is Infinetics $\mu$-metal. The size of the Astrid sensor was 45.4 x 53.4 x 33.0 mm and its weight was 150 g. The CSC was somewhat larger, its outer dimension was about 90 mm and its weight 350 g. The magnetometer has a total weight of 2 kg (Size: 91 x 144 x 193 mm) and is powered with 28 V, 6.5 W. The measurement range is +/- 52000 nT.
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Figure 5.1: Black Brant XII 40.011 UE Vehicle Configuration.
Figure 5.2: Black Brant XII 40.011 UE Payload Configuration. On the upper right is a sketch showing how the three payloads (from top: Mother, Daughter and Baby) would appear without the rocket skin and deployed beams.
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