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MINIMUM HARDWARE NAVIGATION CONCEPT FOR LEO SATELLITES USING INFORMATION FUSION

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Abstract: Improved operational autonomy is required for the operation of any single satellite within a LEO satellite network. One onboard function, which is an interesting candidate to be implemented with an increased level of onboard autonomy is apparently the navigation function, which is in charge of the determination of the instantaneous satellite orbital position and attitude.

This paper aims to demonstrate the capabilities of a minimum hardware configuration which could be an interesting candidate for the cost optimized implementation of the onboard navigation function. The hardware baseline consists of one integrated GPS/GLONASS receiver as primary equipment for nominal operation. Backup navigation is based on magnetometer measurements of the geomagnetic field and real-time processing of landmark images which are provided by a payload earth observation camera. The fusion of the different information sources is performed by advanced filtering and estimation methods.

First results are presented which have been derived from the *TUD-Satellite* demonstration mission "*Satellite based Monitoring of Mobile Objects*" as application reference. This mission uses an earth observation camera for road traffic monitoring purposes and allows perfectly the maximum use of payload resources in the sense, that both the camera as sensor device and a large part of the follow-on image processing software can be used "free of charge" for the generation of navigational landmark data.

The paper discusses the overall system architecture, different filtering options and gives performance results verified by simulation for both nominal (GPS/GLONASS) and backup (magnetometer/landmark) operation.

Keywords: autonomous navigation, GPS, GLONASS, landmark, magnetometer, information fusion, image data reduction, gyro-less navigation

Introduction

Problem Description

Low Earth Orbit (LEO) Satellite Networks offer completely new commercial and technological potentials in the area of global information networking (e.g. GLOBALSTAR, IRIDIUM). This new scenario generates also quite new requirements on the producers and operators of such systems: the change from single to multi-spacecraft production and operation under rigid commercial constraints. These requirements imply cost optimized solutions for both spacecraft production and spacecraft operation. A minimization of the operational cost can be realized by increasing the onboard autonomy for nominal and off-nominal operating conditions. As a consequence the mandatory minimization of spacecraft unit costs becomes much more difficult: besides the reduction of current cost figures this new type of spacecraft has to be equipped even with increased onboard functionality.

This challenging task can be solved only by using novel concepts and techniques to take into account the specific characteristics of the low earth orbit and the satellite network scenario.

The research project* presented in this paper deals with novel concepts for the cost optimized realization of the mission critical function named "*onboard navigation*" for such LEO-satellites. This function is in charge of the autonomous (i.e. without ground support) determination of the instantaneous spacecraft orbital *position* and *attitude*. A reliable and accurate provision of this information is mandatory for the

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**funded by the European Community under contract INTAS-96-2156* basic tasks of spacecraft attitude stabilization and control, spacecraft orbit control (as subtask of network constellation maintenance) as well as for the general payload management (communication, earth observation, etc.).

State Of The Art

Conventional implementations of the navigation function use specific equipment for each sub-function (position, attitude) and *explicit hardware redundancy* (i.e. at least 2 identical hardware devices) to cope with equipment failures. These concepts offer the best performances in terms of accuracy, availability and operational freedom, but suffer from high overall cost in terms of monetary value, electrical power, mass, space, testing and engineering effort. They are therefore not the best candidates for *cost driven commercial* systems. First attempts to build simpler and thus cheaper spacecraft can be found for example in the GLOBALSTAR project. Due to cost reasons this satellite type is the first commercial one in the world, which is going to have a gyro-less onboard navigation system . But in most commercial satellites still conventional concepts based on hardware redundancy and dedicated navigation equipment are used. *Image based navigation* for spacecraft has been realized on a broader level only in the field of attitude determination by using a star tracker systems. Similar concepts, where only a few well known patterns are processed, are currently in development for rendezvous and docking purposes (e.g. ESA). Image processing of more complex landscape patterns is only operational up to now within remote sensing systems (e.g. MOMS), whereas real-time implementations are still existing only at laboratory level (e.g. vision based navigation for spacecraft landing).

Novel Approach

The objective of the novel approach is to *reduce* the *overall cost* for the realization of the navigation function (see above) by a *reduction* of *the total number of hardware devices* (⇒ *minimum hardware approach*) and *substitution* of hardware functions and hardware redundancy by *advanced data processing techniques* (⇒ *information fusion*).

The approach is based on the *"maximum-use principle"* of any onboard equipment, i.e.

P1 use of any single navigation specific equipment for both position and attitude determination, e.g. GPS receiver, magnetometers

P2 use of secondary equipment, originally not assigned for navigation purposes, e.g. earth observation cameras (optical secondary payloads may be interesting for LEO communication satellites, because they can provide an additional information which can be distributed on a commercial basis by the network owners).

Principle (P1) supports effectively the hardware minimization for nominal operation (only *one* single primary navigation equipment is used, e.g. GPS). To cope with failures of the primary navigation equipment, the combination of principles (P1) and (P2) creates the attractive potential of *functional redundancy*. In such a case a combination of secondary sensors (cheap / simple / reliable / available) and advanced data processing will *substitute* the primary equipment. In the proposed concept the backup navigation relies then completely on the fusion of geomagnetic and image based measurements.

Key topics of a joint research project[9], which investigates the capabilities and potentials of such a navigation concept, are the development of the appropriate methods and algorithms to realize such a minimum hardware system. These include research activities in the following areas: GPS/GLONASS based navigation (using novel Russian receiver technology), magnetometer based navigation, landmark navigation principles, landmark feature recognition, real-time landmark image processing, robust information fusion techniques for heterogeneous error characteristics of measurement, optimized observation strategies taking into account cloud cover of the earth surface, analysis of satellite network constellation performances.

This paper presents first results which have been derived from the TUD-Satellite demonstration mission "*Satellite based Monitoring of Mobile Objects*" as application reference. This mission uses an earth observation camera for road traffic monitoring purposes and allows perfectly the maximum use of payload resources in the sense, that both the camera as sensor device and a large part of the follow-on image processing software can be used "free of charge" for the generation of navigational landmark data.

Navigation Concept

Reference Hardware Baseline

The onboard equipment of the minimum hardware navigation system comprises the following devices (see Figure 1):

(A) One integrated *GPS/GLONASS receiver* which acts as the sole device for the determination of both position and attitude of the satellite in the nominal mode of operation;

(B) One *3-axes magnetometer* used as a highly reliable backup device for coarse estimation of position and attitude at any moment of time with arbitrary initial conditions for the estimated parameters;

(C) One *Earth Observation (EO) camera* used as a payload device (including the payload specific image processing software) and available for more accurate estimation (in comparison with magnetometer) of position (and possibly attitude), whose operation is restricted by both environmental factors such as illumination, type of terrain, clouds and non-availability for navigation tasks because of earth observation tasks.

(D) Two redundant *onboard computers* which have to run the estimation and fusion algorithms as well as some image processing algorithms

(E) Two redundant *serial data busses*, which allow to connect any navigation equipment with any of the two onboard computers.

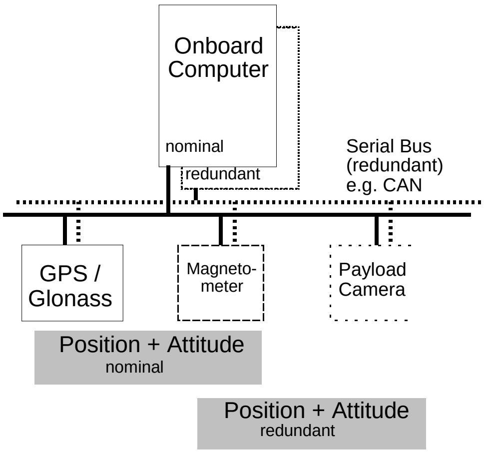


Fig: 1 Reference Hardware Architecture

Besides the EO-camera all devices of this reference architecture belong to the *standard equipment* of a typical LEO telecommunication and earth-observation mission.

Any commercial mission tends to minimize the risk by adding some auxiliary sensors, e.g. horizon sensors, sun sensors, gyros etc., to cope with all operational requirements. In this sense this reference minimum hardware concept does *not claim* to be *the unique optimal solution* for any operational mission. The aim is rather to show the real *capabilities* and *limiting performances* of such a configuration. These results will help to find the appropriate (minimum) level of auxiliary devices and will help to assess the level of mission survivability in case of unexpected failures (e.g. double equipment failure [11]).

The availability of an *EO-camera* as payload is obvious for an earth observation mission. But it could be applicable on certain future LEO missions as well, which combine telecommunication and continuous earth observation (EO) monitoring tasks, i.e. traffic monitoring[10,19]. In these applications as well as in classical EO missions the EO-camera can be used quasi "free of charge" for navigational purposes. This is the reason why it is included in the reference hardware baseline.

Cost reduction cannot only be realized by using minimum hardware configurations. A second approach is to *reduce* the *cost per device*. An interesting low cost but nevertheless reliable option for the *serial data* bus is the automotive CAN bus (Control Area Network). This bus has shown a large conformity with functional LEO satellite mission requirements[3] and will therefore serve as reference baseline for the performance evaluation in the project.

Navigation Functional Decomposition

The *navigation function*, as understood in the frame of this paper, is in charge of the determination (estimation) of the *complete spacecraft state* of motion, i.e. *position, velocity, attitude* and *angular rate*.

The rotational state estimates are mandatory for attitude stabilization and control, whereas the translational states (orbit parameters) serve mainly the orbit control and payload services (mission timeline).

The proposed Reference Hardware Baseline supports a large envelope of operational requirements for a typical earth-oriented LEO mission (tele-communication, earth observation).

Autonomous attitude acquisition from any initial orientation is supported solely by the magnetometers[5] whereas for earth pointing phases (nominal mission operation) all three sensor devices will be usable.

The *software functions* comprise the *preprocessing* of the sensor data and the navigation *filtering algorithms* (see Figure 2). The most complex part of the data preprocessing must be allocated for the image processing functions including landmark recognition. To reduce the amount of extra software for landmark recognition, it should be recognized, that the proposed concept assumes the camera to be an integral part of the satellite payload. In such a case, a lot of image processing software could be reused, if appropriate navigational landmarks are used.

The main navigational software functions comprise:

- GPS/GLONASS navigation is used for nominal navigation.
- Magnetometer navigation is used for initialization and backup navigation.

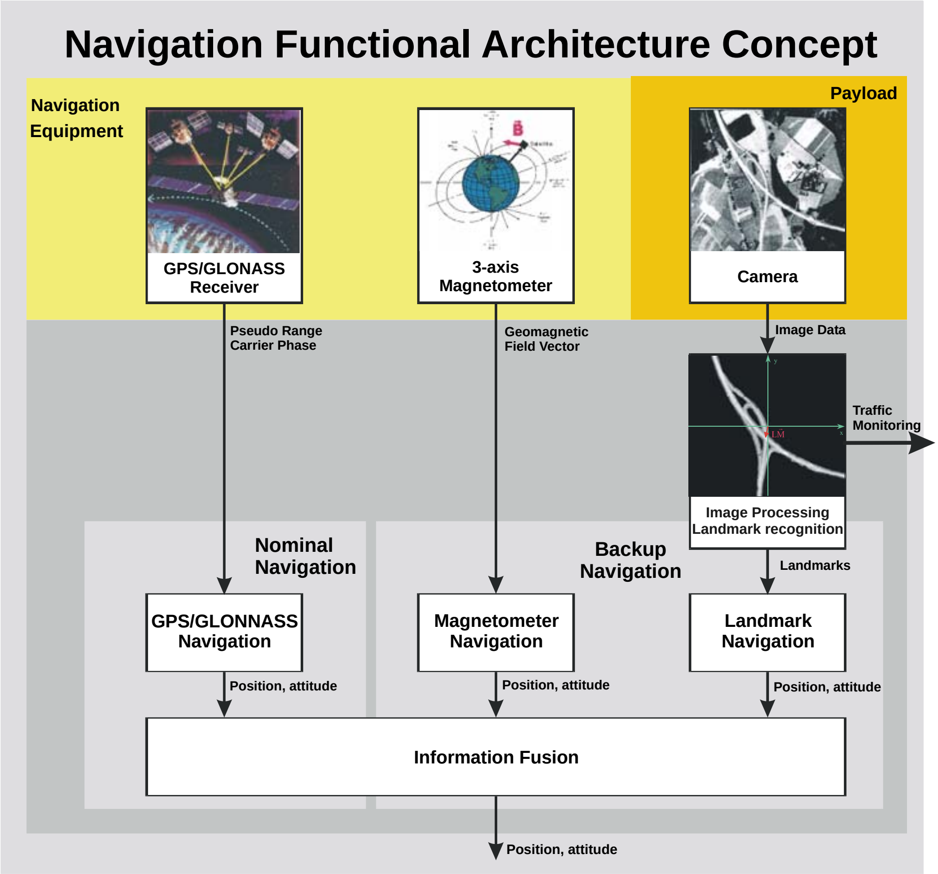


Fig. 1 Navigation Functional Architecture Concept

- Landmark navigation is used for backup navigation.
- Information fusion algorithms are used to achieve best estimation results of the different information sources.

GPS/GLONASS Navigation

GPS/GLONASS Navigation is based on the utilization of the advanced Russian multi-channel integrated GPS/GLONASS receiver technology. These receivers allow to process simultaneously the signals from both types of navigation satellites, NAVSTAR-GPS and GLONASS.

A simplified diagram of the addressed receiver architecture is given in Figures 3 and 4. The following notations are used in the mentioned figures: fg_1 and fg_2 are frequencies of the corresponding heterodynes; the specific frequency of either GPS or GLONASS can be selected as the reference one to synthesize the frequency of the 1st heterodyne; C_1+jC_2 is complex digital video frequency; f_{ref} is the 40 MHz reference frequency; $f_{sampling}$ is the 20 MHz reference sampling frequency.

A simplified diagram of the on-board software architecture and a list of the corresponding software are given in Figure 5.

Well known procedures are applied to solve the navigation problem of the center of mass, including the procedure of GPS/GLONASS constellation integrity analysis, cooperating satellites constellation optimization, secondary data processing, etc. As a reference procedure for the attitude determination problem an algorithm has been adopted which is based on the second differences of the measured pseudoranges.

The main *advantages* of GPS/GLONASS navigation are:

- redundancy of involved navigational satellites belonging to both GPS and GLONASS constellations,
- absence of Selective Availability mode of operation by GLONASS navigation,
- more favorable observability of GLONASS satellites (compared to GPS) for typical LEO missions.

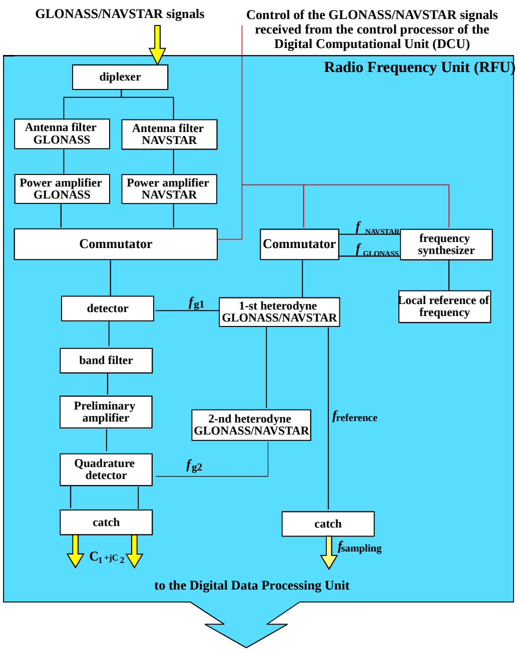


Fig. 3 Simplified diagram of the RFU

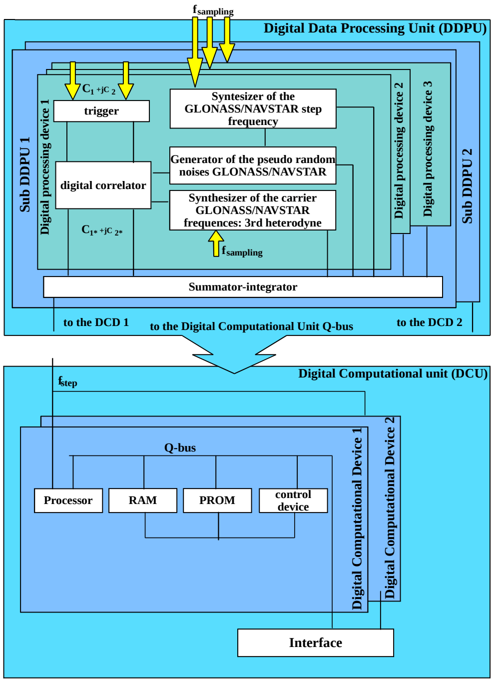


Fig 4. Simplified diagram of DDPU and DCU

The main *disadvantages* are:

- necessity to have an on-board backup navigation system in order to provide coarse position, velocity, and attitude estimates to obtain initial data for the GPS/GLONASS attitude determination procedure,
- necessity to have an on-board antenna system (3 or 4 antennae) and in consequence 3 or 4 different receivers (RFU) for the attitude determination problem
- short length of the GPS/GLONASS antenna baselines on small satellites, influence of satellite body distortion and multi-beam effect as unfavorable factors for the attitude determination problem.

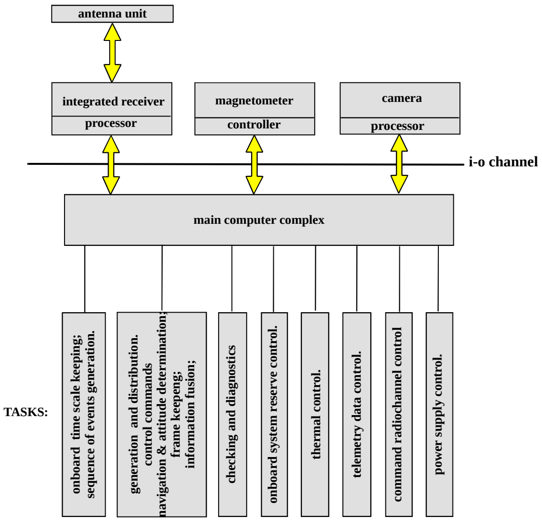


Fig. 5 Flowchart of the GPS/GLONASS on-board software

Magnetometer Navigation

Magnetometer navigation is based on measurements of the geomagnetic field vector by a magnetometer. It is supposed to use magnetometer data as an additional measurement source during acquisition phases or as a backup when the GLONASS/GPS receiver has failed. Autonomous navigation using magnetometers is a problem actively studied worldwide during the last several years[6, 12, 17, 18]. Magnetometers have proved to be very reliable, small, and cheap devices that provide the capabilities to determine both position and attitude of the spacecraft. Moreover, the autonomous navigation process based on magnetometer has almost absolute stability even with very bad initial estimations: the estimation converges to its stable state even from initial errors of hundreds of kilometers and unknown attitude within some few orbits.

The main error sources for magnetometer navigation can be grouped in equipment and spacecraft related errors (noise, biases, geometrical offsets, strawfields from other onboard devices) and errors due to the uncertain knowledge of the geomagnetic field. Commonly a frequently updated IGRF model (International Geomagnetic Reference Field) is used, which does not take into account some stochastic disturbances of the magnetic field (e.g. magnetic storms). Although some studies claim achievable

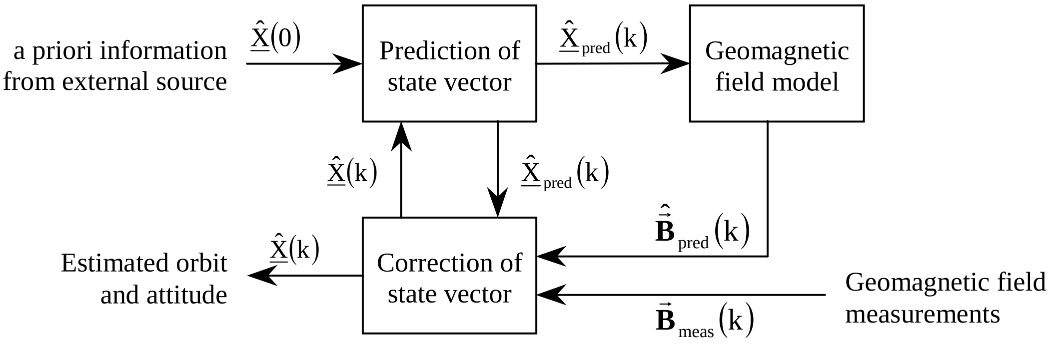


Fig. 6 Flowchart of the magnetometer navigation

accuracies of magnetometer positioning at the level of 1-2 km and attitude determination with 0.25 degrees. Figures obtained under more realistic conditions and cited by the majority of researchers are tens of kilometers for positioning and several degrees for attitude determination.

The magnetometer navigation is based on the mathematical description of the geomagnetic field as spherical harmonics with

$\mathbf{B}(r,\theta,\phi)$	Geomagnetic field vector
$r,\ \theta,\ \phi$	Position in spherical coordinates

The processing of the measurements can be performed in two ways:

(1) *magnitude measurement* of $\mathbf{B}(r,\theta,\phi)$
  - requires no attitude information
  - supports position estimation (orbit parameters) only
  - simple algorithms and lower convergence speed

(2) vector measurement of $\mathbf{B}(r,\theta,\phi)$
  - supports position and attitude estimation
  - requires attitude information for pure position
  - estimation
  - more complex and higher convergence speed

The filtering approach follows well known Extended Kalman filtering (EKF) techniques[1, 6, 18] which are based on orbit models of appropriate complexity. A simplified flowchart is given in Figure 6.

The main *advantages* of magnetometer navigation are:

- magnetometers are reliable and robust sensors,
- no pointing requirements for the satellite ("blind-sensor"), as e.g. landmark navigation
- requires no a-priori attitude information.

The main *disadvantages* are:

- low accuracy, significantly worse than the accuracy provided by use of GPS/GLONASS technology and worse than Landmark navigation
- necessity to calibrate the magnetometer and algorithms before the system works with the best possible accuracy (estimation of some systematic errors).

Landmark Navigation

Landmark navigation is based on the comparison of the images obtained by an on-board earth observation (payload) camera and the images of the same areas of the earth's surface stored in the on-board computer.

The solution of the spacecraft navigation problem using ground landmarks is based on the principles considered in detail in [8, 14, 15]. Briefly, the concept of landmark navigation consists of the following steps (see Figure 7):

- on the ground, before flight, a landmark database is formed. The landmarks must be stored with their coordinates determined in the Greenwich reference frame.
- during the flight current images (obtained by the camera) are formed periodically.
- reference images are generated using landmark database by the on-board computer for the same moments of time.
- the current and reference images are processed together to identify corresponding elements (landmarks); coordinates of the landmarks in the current image are determined.
- navigational angles are formed and based on the results of image processing.
- they are fed into a Kalman-type filter along with current estimates of the spacecraft state vector and predicted values of the navigational angles to correct the state vector.

There are many various ways to form the navigational angles[14]. For the TUD-satellite reference mission, it is expedient to form them as three angles between the

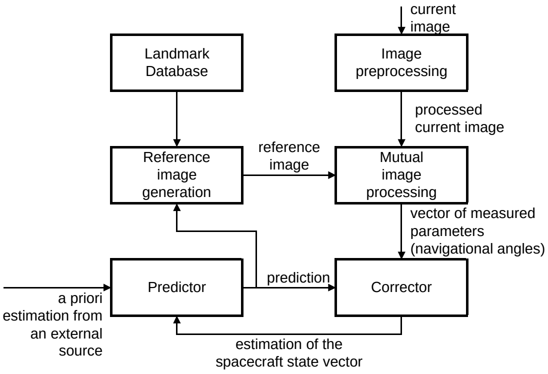


Fig. 7. Flowchart of landmark navigation

directions between the lines-of-sight of three landmarks discovered in one image (see Figure 8).

The main *advantages* of landmark navigation are:

- only the camera and on-board computer are used; no necessity to use additional on-board equipment dedicated for navigational purposes (in accordance with the minimum hardware principle)
- comparatively high accuracy (better than magnetometer navigation and some other methods of autonomous navigation).

The main *disadvantages* are:

- high requirements on the performance of the on-board computer (large memory required for landmark database,real-time image processing)
- requires camera nadir pointing
- asynchronous measurements due to landmark visibility constraints (available database, cloud cover), which may result in long filter propagation periods
- requires camera and algorithms calibration before the system begins work in nominal mode
- accuracy is significantly worse than accuracy provided by use of GPS/GLONASS technology.

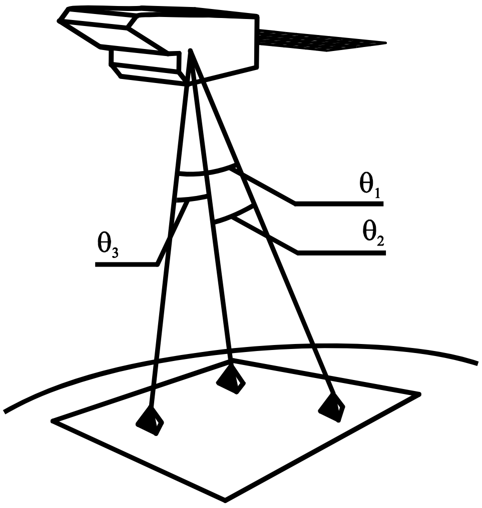


Fig. 8 Navigational angles

Information Fusion

In principle any of the baseline navigation techniques as described above is capable to solve the navigation problem autonomously. However due to the different performance and operational characteristics of each technique it is expedient to fuse all of the available (redundant) information to reduce the overall navigation error. In the considered gyro-less autonomous spacecraft navigation system the *information fusion techniques* are used for the following purposes [13]:

- In the *initialization mode* the coarse estimation of the spacecraft state vector obtained by magnetometer and/or camera measurements is used to resolve the initial ambiguity problem for the GPS/GLONASS attitude determination.
- In the *nominal mode* of operation the very accurate information from the GPS/GLONASS receiver is used to calibrate the navigation algorithms, camera and magnetometer.
- In the *backup mode* of operation the navigational measurements are provided by the magnetometer and camera which complement each other: the camera provides accurate asynchronous data, whereas the magnetometer provides coarse but continuous data during the long intervals between landmark measurements.

The *fusion algorithms* (i.e. optimal estimation filtering algorithms) have to take care for rapidly changing errors, systematic errors with known variance functions as well as indefinite errors with unknown statistical characteristics varying within known boundaries. Moreover some of the errors are strongly correlated (e.g. magnetometer position/attitude). For this type of problem the conventional Kalman-Filter based approaches have to augmented by special provisions or replaced by dedicated filtering techniques, e.g. *unified approach* based on recurrent Bayesian estimation algorithms adaptive to various uncontrollable factors[15]. Moreover an adequate balance between centralized and decentralized fusion has to be found[4].

Reference Application Mission

Mission Objectives

Today, almost all LEO satellite networks under development are market-driven, commercial systems concentrating mainly on either telecommunication or navigation services. In order to increase the use of these networks it would be beneficial to add additional payload functions such as Earth observation. This would open new commercial application fields like traffic telematics, road traffic management and traffic data acquisition. There is an increasing economic importance of these emerging services with an estimated value of 80-100 billion DM in Europe during the years 1997-2010. Unfortunately, the bottleneck for traffic information services is the gathering process for traffic information.

The Dresden University of Technology tries to fill this gap by developing a demonstration satellite to show the feasibility of gathering satellite-based traffic data[10, 19]. In the frame of the demonstration mission using a single micro-satellite (TUD-Satellite), the project team intends to collect and provide data through a number of field test campaigns. This data will be used as an additional input to commercial traffic data providers.

The demonstration mission objective is to provide in near-real-time commercially relevant information for traffic and environmental monitoring with the following characteristics, Fig 9:

- Monitoring of anonymous or identifiable mobile objects (clients) on the Earth's surface (particularly cars), including geographical areas with less developed infrastructure.
- *FCD (Floating Car Data)*: The monitoring is based on *primary data* derived from *active (co-operative)* clients, which transmit client-related status information via RF links to the satellite. Those data sets comprise information on vehicle position and velocity, derived from commercial on-board car navigation systems.
- The monitoring process is supported by *secondary time-synchronous and complementary data*. This data is obtained from observing both active (co-operative) and passive (non co-operative) clients by means of a *spaceborne optical high resolution camera*.
- The complete set of collected data (i.e. FCD data & image) is transmitted to a ground-based information processing centre. There, it is processed at different levels of aggregated (high level) information e.g. individual monitoring of identifiable clients and public traffic status monitoring.
- The derived high level information shall be available for distribution in near-realtime by commercial information service providers, e.g. radio traffic news services.

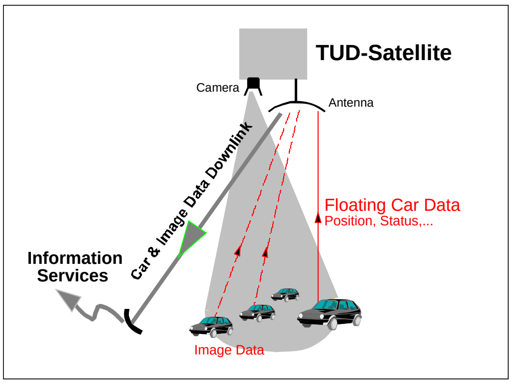


Fig. 9: Demonstration Mission Overview

The scientific goals for the development of key technologies, derived from requirements for LEO satellite networks, are:

1. *Development* of appropriate *methods and algorithms* to accomplish the mission tasks:
   - system design for combined telecommunication and Earth observation on-board functions
   - information augmentation through processing of complementary image and radio data (*information fusion*)
   - Earth observation based on processing of sub-pixel information
   - real time algorithms for on-board data classification, data reduction and data compression

2. *Development* and *demonstration* of *cost optimized* satellite *technologies* for LEO satellites based on innovative system solutions:
   - failure tolerant architectures based on *functional redundancy*, e.g. on-board autonomous navigation using payload data and information fusion techniques
   - electronically controlled planar antennas
   - demonstration of applicability of industrial technology (technology spin-around) for the
     - space segment, e.g. automotive components like CAN-bus, sensors, microelectronics
     - ground segment, e.g. commercial process control and visualization technology, web-based monitoring.

TUD-Satellite Characteristics

Orbit:

The proposed satellite orbit shall allow for a frequent observation of central Europe, in particular Germany. Therefore, a circular orbit with 500 km altitude and an inclination of 53° was chosen. As the spacecraft has no propulsion system, the estimated orbit lifetime is limited to approximately two years. The satellite is planned to be launched as a secondary or "piggy-back" payload.

Platform:

Attitude control system:

- passive gravity gradient stabilization
- active bias momentum stabilization
- active magnetic control via magnetorquers
- GPS/GLONASS receiver
- 3-axis magnetometer
- earth horizon sensor

Structure:

- 1000 x 800 x 800 mm,
- CFRP sandwich panels with four CFRP tubes

Data-Downlink:

TM	9,6 kbit/s	P-Band
Payload Data	2 Mbit/s	S-Band

Data-Uplink:

TC	9,6 kbit/s	L-Band
Vehicle Data	250 kbit/s	L-Band

Mass: 107 kg
Power (mean / max): 47,08 W / 80,65 W

Payload

- *FCD Traffic data communications:* The data packet generated by each co-operative vehicle has a length of 100 bit. All vehicles send their data packets to the satellite. Onboard the satellite is a fixed-phase patch antenna with a swath of 100 km to receive the vehicle data.
- *EO-Camera:* The proposed camera[7] has a panchromatic ground resolution of 2 to 2.5 metres per pixel from orbits of 500 to 800 km. The heart of the camera is a 7k x 8k Philips CCD sensor with 12 μm sensor elements. An envisaged 500 km circular orbit results in a swath width of 10.25 km. The camera is light-weight (8 kg, including CCD and detector electronics).
- *On-board data processing:* Due to the high volume of data generated by the on-board camera (66 Mio. pixel per image) and the limited downlink channel capacity (2 Mbit/sec), the image data must be reduced thematically by a factor of 100 to allow a near real-time image data transmission. A data reduction algorithm has been developed and implemented to accomplish this task in real-time[16].

Application Results

Nominal Operation using GPS/GLONASS

Algorithms for determination of position, velocity, and time are known very well nowadays and implemented in various space vehicles. Therefore we will concentrate in the following only on the peculiarities of the concrete implementation of such algorithms.

It is known, to solve the navigation problem the following actions have to be performed:

- search of satellite signals
- capture of signals
- signals tracking

and simultaneously providing receiving and decoding of the service information. Besides, we have to compensate ionosphere refraction (for spacecraft application) as well as to provide correction of the measurement results due to correction to the time scale and on-board generator frequency of each cooperating satellite.

Almanach data, also transmitted in the message, are used both for the working constellation selection and for signals search and tracking. The position and velocity components of each navigation satellite at the measurement time instant are computed by short term propagation, using ephemeris information. To solve the navigational problem itself, various data processing algorithms can be used, such as Kalman filter or Least Square Method modifications.

All above listed operations, which should be implemented during every single navigational session, can be provided by the following set of subroutines (modules), controlled by the main dispatcher:

1. Selection of the working constellation to determine the number of satellites suitable for the navigational problem solution. Input data: system almanac and prior data about vehicle position and current time. Output data: satellite numbers.
2. Prediction of the navigational parameter to calculate expected values of the pseudorange and pseudorange rate. Input data: prior estimated position of vehicle and predicted position of navigational satellite. Output data: predicted value of navigational parameter to point signal search by using C/A code.
3. Receiving and processing the service information to format the system almanac, the ephemeris, the time and the frequency corrections selection. Input data: navigational message. Output data: system almanac, ephemeris, time and frequency correction.
4. Short term ephemeris propagation to compute precise position and velocity of the navigational satellite at the measurement time instants. Input data: satellite number, time instant, position and velocity of the satellite, corresponding to ephemeris data at the nearest time instant. Output

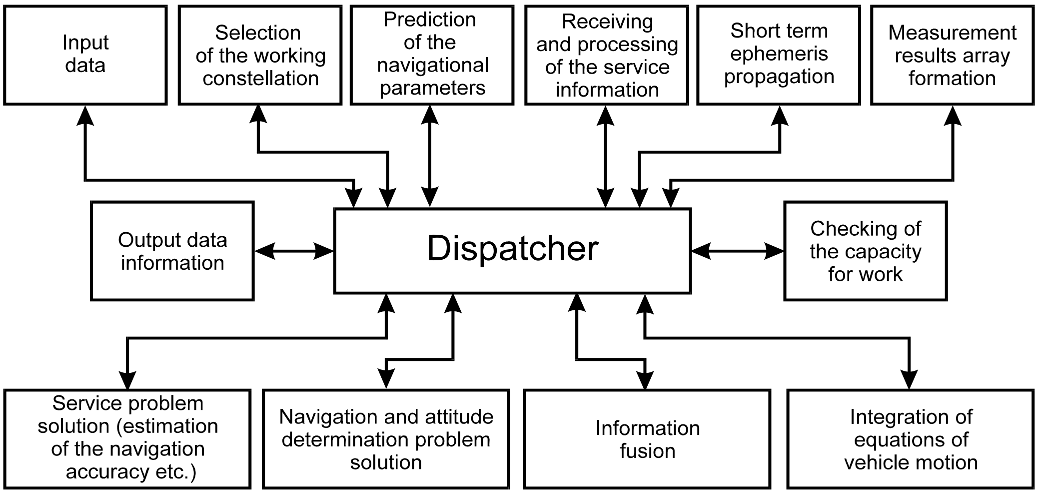


Fig. 10. Simplified diagram of the on-board GLONASS/GPS software arrangement

data: precise position and velocity of satellite.

1. Service problems to calculate Formation of the measurement results array to correct measurement results according to time scale, frequency and ionospheric delay corrections. Input data: measurement results, obtained from the satellite tracking channel and correction values, obtained from the navigational message. Output data: corrected measurement results array.
2. Determination of vehicle position, velocity and current time in the GLONASS/GPS frame. Input data: measurement results array. Output data: position, velocity and time of vehicle, precise values of the ephemeris.
3. posterior covariance matrix and estimation of additional navigation parameters. Input data: prior covariance matrix, vehicle position and velocity vector. Output data: posterior covariance matrix and estimation of additional navigation parameters.

All above listed procedures can be illustrated by Figure 10.

We will consider the problem of the satellite attitude determination as problem of the antenna system baselines (see Figure 11) attitude determination relative to the axes of reference frame. Any frame can be accepted as the reference frame, for instance, absolute inertial reference frame. The problem of the baseline attitude determination consists in comparison to the navigational satellites signals arriving time instants at the A_i and A_j points of the baseline.

We suppose that receiving antenna, situated at the A_i and A_j points of the baseline tightly fixed to the satellite body. Satellite attitude relative to the reference frame can be described using various parameters, for instance, directing cosines, quaternions, Euler's angles, etc. We will use for our purpose directing cosines.

It is known that second differences of the pseudoranges of two navigational satellites, which depend on directing cosines are being defined, is a function of second differences of the carrier phases of signals from the mentioned satellites.

The specific feature of the phase differences measurement is restriction of the phase difference in the range [0,2π]. To perform this measurement process it is necessary to develop a so called counter (indicator) of the integers of the signal periods. This counter should indicate output +1 or -1, if the magnitude of the phase difference reaches the value 0 or 2π, correspondingly. This counter is in fact the essence of the attitude determination algorithm.

The preliminary simulation results will be presented the possible accuracy of attitude determination in dependence on the baseline length (Figure 12) as applied to the near-circular orbit with altitude not more than 1000 km.

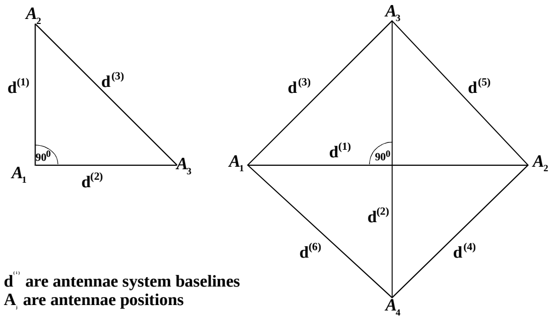


Fig. 11 Antennae system configurations

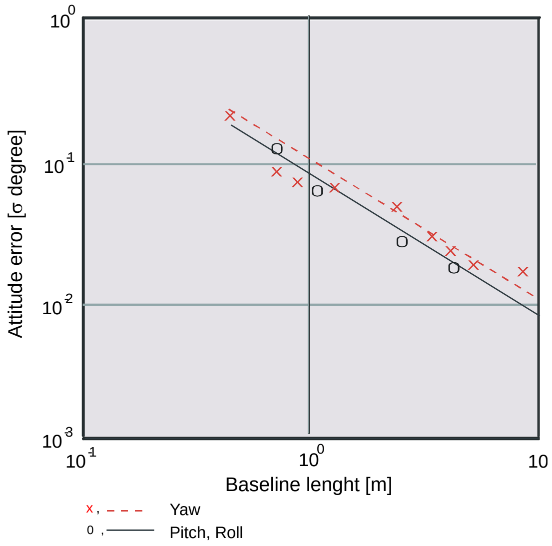


Fig. 12 Preliminary estimation of GPS/GLONASS attitude determination accuracy

Backup Position Estimation using Magnetometer

Many influences of the accuracy of the geomagnetic field measurements are known. They can be divided into two classes:

- geomagnetic field *disturbances* e.g. drift, magnetic storms
- measurement *errors*, e.g. noise, misalignment, bias, quantization of the A/D-converter

A rough order of magnitude (ROM) estimation of the maximum RSS position estimation error of magnetometer navigation depending on the disturbances can be derived from a standard dipole model of the magnitude of the geomagnetic field vector[20] (see Figure 13).

$$\left|\vec{\mathbf{B}}\right| = \frac{\mu_{ME}}{R^3}\sqrt{1+3\sin\theta}$$

with	μ_{ME}	Earth magnetic moment (7.805*10^{15} gauss/cm³)
	R	distance satellite – Earth centre
	θ	Latitude (0° = equator, 90° = pole)

A *baseline position estimation filter* has been implemented using optionally the *magnitude* or the *full vector* information of the geomagnetic field. The filter design follows a well known approach[18] which is based on an Extended Kalman Filter with an orbit model using Keplerian elements. For the TUD-Satellite reference mission the measurement errors are dominated by Gaussian errors and constant systematic errors, which justifies the application of

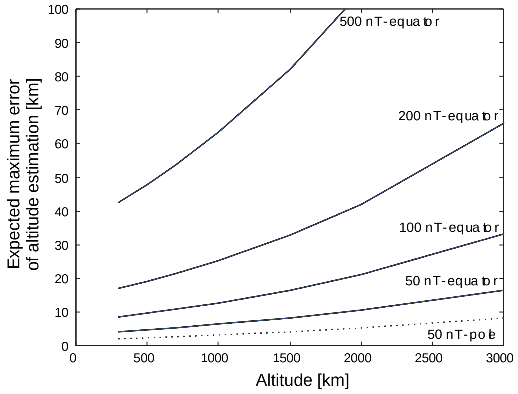


Fig 13 Maximum RSS estimation error

EKF-techniques[2]. The estimation performances are in accordance with the results given in [18] and result in typical RSS average position errors in the order of 8-10 km (see Figure 14). The evaluations show clearly the limitations of *sole* magnetometer navigation in reaching operational performances comparable with the nominal ones.

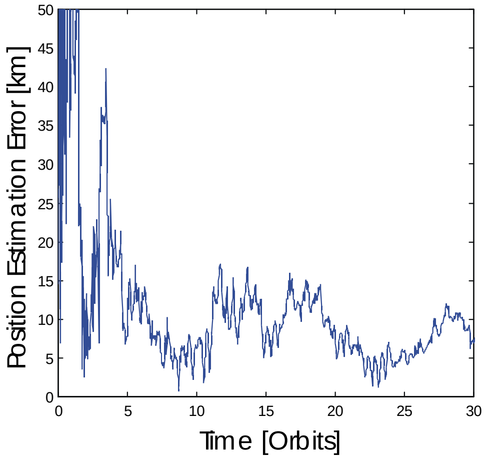


Fig. 14 Simulation results using measurements of the magnitude of the magnetic field

Landmark Recognition and Processing

The main drawback of landmark navigation is the high computational load for the processing of landmark related information. As the landmarks have to be derived in realtime from onboard image data, appropriate algorithms and software functions have to be provided for navigational purposes.

Dedicated navigation cameras may therefore not be the best candidates for minimum hardware concepts, because a lot of onboard computer and mass storage capacity is required in addition to the camera hardware.

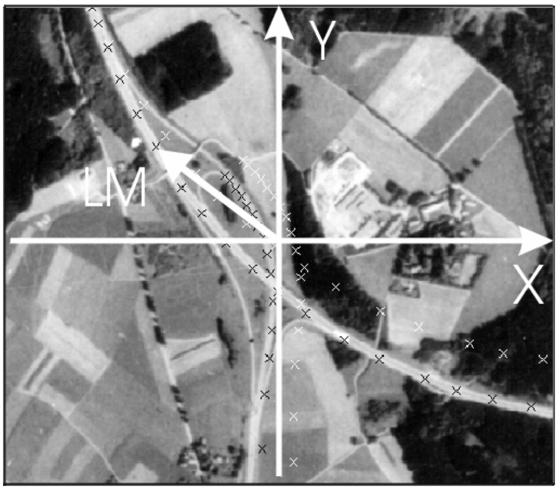
However if the payload earth observation tasks incorporate already some thematic preprocessing of the images then the extra effort for navigational image processing can be reduced considerably. This is just the case for the TUD-Satellite reference mission.

For the purpose of *road traffic monitoring* the most important information is contained in the roads itself. It is therefore sufficient to downlink only those parts of the images, which contain road data. This reduces tremendously the required downlink budgets up to a factor of 100.

A thematic data reduction algorithm has been developed for this purpose, which allows to mask out the road information from the image[16, 19] (see Figure 15).

The method requires a consistent data set of the road middle axis (vector reference) augmented by a local estimation of the road width and a global estimation of the mean grayvalue of the road surface. They are stored as GIS-vector (GIS-Geographic Information System) reference data in the on-board computer. Starting with a rough estimation of the actual position and pointing of the satellite, an a-priori pixel structure of the roads in the image is calculated. The iterative matching process recognizes typical road image patterns and compares them to the a-priori pixel structure using a potential field derived from a target-specific filtered image. After the successful matching all other image informations are masked out.

It is now obvious to use this road data directly as landmarks, because all prerequisites for landmark generation are fulfilled perfectly. The landmark navigation requires information on the position of the landmark (= road) on the ground and the position of the landmark in the current image. The position on ground is stored in the GIS-vector on-board reference and the position in the image is calculated from the actual matching process (see Figure 16).



x (white) – a priori Landmark position on image
x (black) – Landmark position on image after matching process

Fig. 16 Landmark generation

Backup Position Estimation using Landmarks

To provide an a priori estimation of the accuracy of landmark navigation depending on various factors, computer simulation of the navigational process has been performed using a specialized software (see Figure 17).

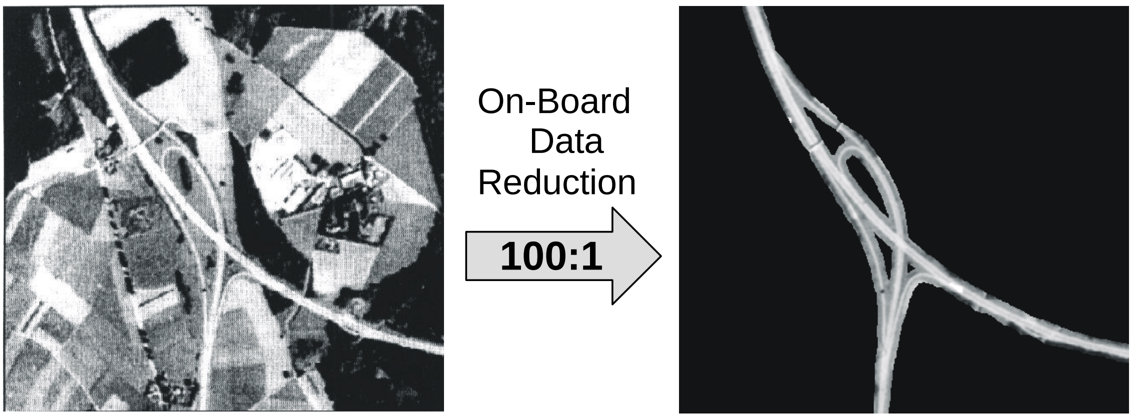


Fig. 15 On-board Processing for Image Data Reduction

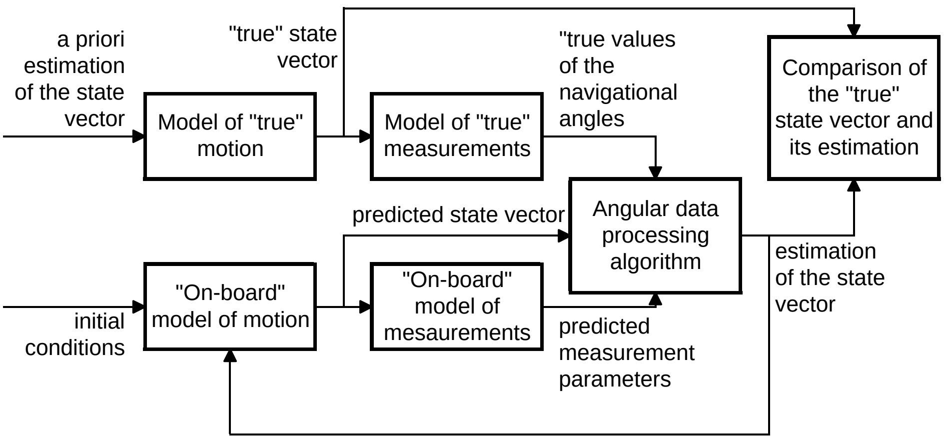


Fig. 17 Scheme of navigational process simulation software.

The navigational angles have been formed according to Figure 8, which are independent from the satellite attitude (this is comparable with magnetometer navigation using the magnitude of the geomagnetic field). A performance evaluation has been performed on the basis of simulation studies taking into account various uncontrollable factors divided into three groups:

- clouds, type of terrain, illumination, etc. that determine the possibility to perform measurements
- errors of angular measurements, caused primarily by errors of image processing
- errors of motion prediction caused by inaccurate initial conditions and difference between «true» and on-board model of motion.

The study demonstrated efficiency of the suggested navigation technique: it works in a very wide scope of orbits, camera characteristics, and other parameters of those models (i. e. the estimation process converges). For the TUD-Satellite reference mission the method provides solution to the navigational problem with a maximum error not worse than 4 — 6 kilometers. The main factors that determine the navigation accuracy (supposing that orbit altitude is fixed) are the camera resolution and field-of view (see Figure 18 and 19).

As for the interval between measurements, its influence is not so important (see Figure 20).

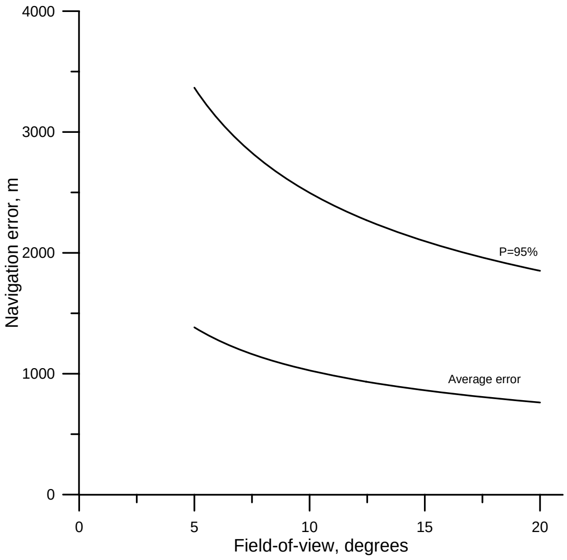


Fig. 18 Accuracy of navigation vs. Camera field of view

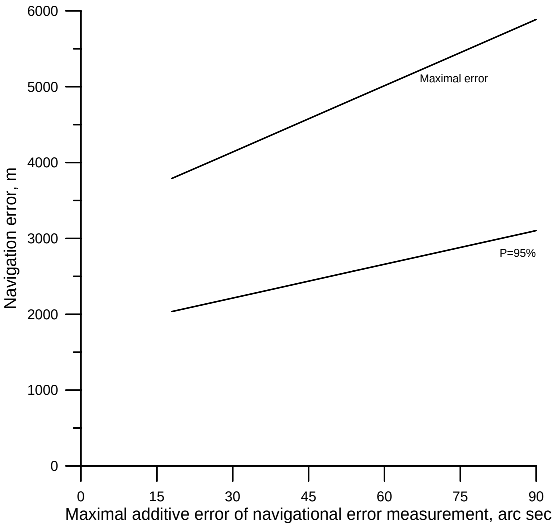


Fig. 19 Accuracy of navigation vs. Camera resolution

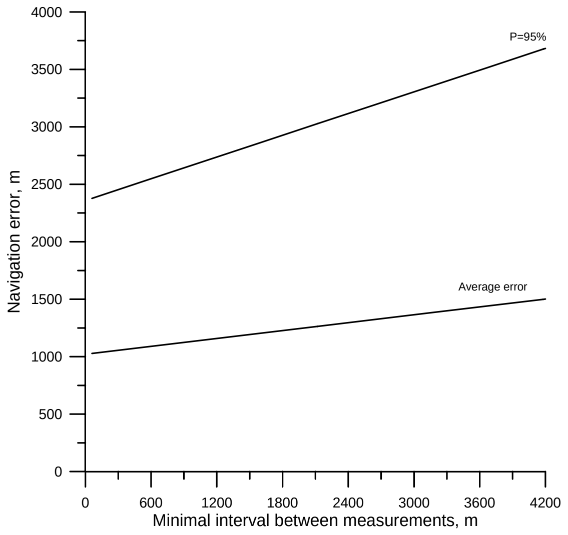


Fig. 20 Accuracy of navigation vs. interval between measurements

Backup Position Estimation using Magnetometer and Landmarks

The study of accessible estimation performances based on the sole use of one backup sensor alone (magnetometer, landmark) shows clearly the limitations of single information sources. Magnetometer based information suffers from measurement errors resulting mainly from geomagnetic field uncertainties. Landmark based information suffers from rare updates due to road availability and disturbing weather conditions (clouds), which results in long filter propagation periods.

Preliminary investigations on the capabilities of fusion of the two backup information sources have been performed for the *position estimation problem*. The investigated fusion algorithm is based on a centralized Extended Kalman Filter, which uses directly the continuously available magnetometer data and asynchronous landmark data[2].

This configuration (i.e. centralized filter with common filter states) is preferred against the fusion of the outputs of the individual magnetometer and landmark navigation filters (i.e. decentralized), because in our case any of the filters would be implemented in the onboard computer anyway. In this case the different measurements can be used directly for the updating of a filter using common states. A different question arises if the GPS/GLONASS based estimates would be used in addition. In this case, the GPS/ GLONASS navigation filter may be located at box level within the receiver and therefore only the state estimates are accessible.

The simulation results for the centralized magnetometer/landmark filter show clearly the benefits of information fusion, because the estimation accuracy improves considerably. A typical simulation result is shown in Figure 22, assuming only *two* landmark updates per orbital period (see for comparison Figure 14, where the same simulation conditions are used for sole magnetometer navigation).

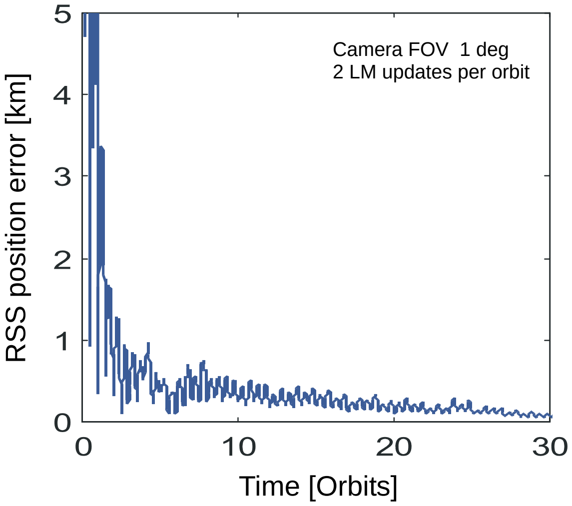


Fig. 21 Fusion of Magnetometer and Landmark Navigation

A generalization of these results is shown in Figure 23, where the dependency of the average RSS position estimation errors on the frequency of landmark updates is given (derived from simulation studies).

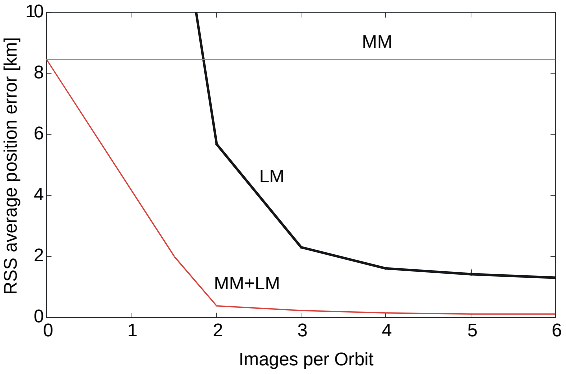


Fig. 22 Preliminary backup position navigation performance based on fusion of magnetometer and landmark data

Current Activities

The ongoing research activities concentrate on the following topics:

- filter design for combined position and attitude estimation (magnetometer, landmarks)
- verification of the magnetometer navigation with real flight data derived from German X-ray satellite ROSAT[11]
- investigation of different fusion methods taking into account in particular the landmark measurement error characteristics (non-Gaussian , bounded errors, uniformly distributed)
- calibration of the backup system (magnetometer, landmark) using GPS/GLONASS measurements
- detailed performance evaluation under representative operational conditions
- set up of an real-time laboratory demonstrator.

Summary

This paper describes a minimum hardware navigation concept for LEO satellites based on the *maximum-use principle* of any onboard equipment. The combination of navigational equipment (GPS/GLONASS receiver, magnetometer), payload equipment (earth observation camera) and subsequent *information fusion* algorithms supports the application of the functional redundancy concept to meet redundancy requirements as well as performance requirements. First results are presented, which have been derived for the TUD-Satellite mission dealing with road traffic monitoring. The results for backup position estimation show the capabilities of information fusion and allow some first estimation on reachable performances. A thematic data reduction algorithm is presented, which supports in an efficient way the resource critical task of onboard landmark recognition and processing.

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