Satellite Network Bavaria – Mission and Data Processing

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Abstract: Agriculture and silviculture as well as governmental institutions are facing major challenges concerning climate change and species conservation. Intensifying extreme weather events add pressure to establish a sustainable management which requires optical geodata with a high temporal and spatial resolution. This also encompasses new demands in the private sector.

Existing missions prove that small satellites can fulfill this demand in an economical manner. Especially the CubeSat standard enables the development of satellites outside of big space agencies and therefore specialized missions that take regional demands into account.

To fulfill its sovereign tasks in the aforementioned disciplines with their current and future challenges, the Bavarian state initiated studies to determine the potential of a small satellite mission. The resulting demonstrator mission comprises a formation of five 6U CubeSats, each equipped with a multispectral camera, to monitor state territory with high resolution and frequency. The mission is executed as a research alliance between the Bavarian surveying administration, the Technical University of Munich, and the Center for Telematics Würzburg. It encompasses the entire process chain, from mission design and satellite manufacturing up to data processing. The publication describes the mission concept, focusing on data processing strategies. Further, a simulator for artificial satellite imagery is presented.

1 Mission Introduction

Earth observation imagery demand and availability is growing rapidly, as pressures from climate change and global market dynamics rise, as well as its list of valuable applications. Conventional earth observation satellites, e. g. Sentinel-1 to -6, are a potent data source but have downsides in long development cycles at a high cost and come with a tradeoff between ground sampling distance (GSD) and ground coverage. Only highly funded agencies can launch singular exemplars. In contrast, with low cost and fast development cycles, CubeSats are an alternative for stakeholders that enables them to tailor satellite missions to their unique needs while remaining affordable. Often, their drawbacks because of the small form factor can be mitigated by adapting mission parameters and launching larger constellations, still costing less than a singular conventional earth observation satellite.

As the most prominent contender, Planet Labs' daily repetition cycle for an almost global, multispectral coverage through the PlanetScope constellation (PLANET TEAM 2017) satisfies the demand for readily available, high-resolution data. Still, its mission design has drawbacks, e.g.,

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concerning image acquisition consistency and data sovereignty. Creating similar acquisition parameters like sun incident angle i.e., constant local revisit time, or utilizing the same satellite for a region repeatedly to enhance change detection algorithms radiometrically, are desirable in remote sensing. In other terms, indelible accessibility to this security-relevant and now vital data is not guaranteed with foreign private companies.

The Bavarian surveying administration (BVV) conducts biannual aerial image acquisition campaigns ("Bayernbefliegung") to obtain very-high-resolution imagery of the free state. The 20 cm GSD RGBIPAN products can be utilized for sophisticated use cases but lack a high temporal resolution, ruling out short- and medium-term change monitoring. Exemplary applications that are not feasible are intraseasonal agricultural and silvicultural products like growth monitoring or natural disaster damage assessment. Increasing flight frequency to a weekly timeframe would result in exploding costs and is therefore not viable.

To assess the potential of a state-owned CubeSat solution for this gap, the BVV conducted preliminary studies together with TUM Photogrammetry and Remote Sensing (PF), Astronomical and Physical Geodesy (APG) and Center for Telematics ("Zentrum für Telematik", ZfT) Würzburg. State agencies were involved to identify stakeholder requirements. Core needs were state-wide coverage, more than five years of lifetime, a repeat cycle of less than five days with consistent local revisit times, a GSD below five meters and a spectral range that supports agricultural and silvicultural applications. Mission parameters and design were derived with the help of simulators.

As state-wide coverage requires a larger satellite constellation, a precursory demonstrator mission was commissioned to verify mission, orbit and satellite design as well as the data processing chain. This demonstrator mission is outlined below, starting with important mission design elements, followed by aspects of the processing chain and composition of the PF simulator. Parameters still might change in detail.

2 Preliminary Mission Design

2.1 Satellites

As this publication focuses on the description of the simulation and data processing systems, satellite engineering and design will only be described in an overview. The constellation encompasses five 6U CubeSats identical in construction. Each carries a multispectral camera outlined in chapter 2.2 as its main payload. To be able to achieve the desired lifetime of at least five years and to maintain the orbit configuration presented in chapter 2.3, they are equipped with a chemical engine. X-band, S-band as well as UHF antennas are used for data downlink, uplink, and TT&C. GNSS antennas provide satellite location data and solar panels on all unoccupied surfaces provide power.

This mission has high demands concerning the ADCS's capabilities for a CubeSat. To keep the total number of satellites needed for a gap-free coverage of Bavaria as low as possible and ensuring an overlap while being economically efficient, satellite orientation has to be determined with high precision. As a coarse measuring instrument, a sun sensor is used. For high precision attitude determination two perpendicularly mounted star trackers are installed. Attitude is controlled via magnetorquers as well as reaction wheels.

One of the biggest challenges in this mission's satellite design is to fit all needed subsystems into the frame as build and launch costs grow with constellation size. A 3U or 4U chassis does not provide the necessary space for all subsystems. This constrain is also reflected in the orbit design, as the available space for the camera's optics limits GSD which can then only be improved by lower orbit heights and therefore more narrow swath widths.

Final satellite assembly is taking place at ZfT.

2.2 Payload

The main payload is an eight-channel multispectral pushbroom CMOS line scanner. Its spectral filters are selected to accommodate for mainly agricultural and silvicultural application purposes in a range of 450 – 900 nm as well as a PAN channel. Each spectral band can use up to 32 TDI stages for improved illumination and image quality in the 10-bit pixels. The lens system offers a field of view of 2.22° at a focal length of 580 mm.

2.3 Orbit

The constellation of five satellites will be flown in a string of pearls configuration on a sun synchronous low earth orbit (LEO) with a repeat rate of roughly three days, passing Bavaria before noon for optimal atmospheric and constant lighting conditions. Once within each repeat cycle, the satellites consecutively capture overlapping image stripes of Bavaria. The center satellite will pass over the east of Munich on a near-polar orbit at a mean height of 460 km, resulting in a mean swath width of roughly 18 km at 4 m GSD. After the satellites acquire the images in imaging mode, they are turned to face the ground stations for data transfer. When data transmission is complete, they are turned back to their imaging configuration. All orbit and orientation maneuvers are executed after imaging, so none are executed during the image capturing overpasses, ensuring a stable and vibration-free environment.

Orbits are designed and calculated by APG and ZfT.

3 Preliminary Data Processing

3.1 Data Processing Chain

The amount of data that is generated by the satellites within a repeat frequency of roughly three days does not allow for semiautomated processing, whether in the demonstrator or in the full extension of the mission. Currently, the BVV processing chain for the Bayernbefliegung contains manual steps to interactively select key points. A fully automated processing chain is being built to ensure timely data handling within the satellites' revisit time.

At data processing level 0, the consistency-checked raw image data is transferred from the ground stations. The IT service center Bavaria is providing the infrastructure for storage and data handling. TUM, BVV and ZfT all provide algorithms for the successive data processing chain. The image preprocessing system for level 1 is laid out in chapter 3.2. Details on processing done by ZfT and APG or subsequential products are not further described within the scope of this publication.

3.2 Data Processing Level 1 A&B

After the initial preprocessing of the bit-wise raw data, geometric and radiometric corrections are applied. Radiometric calibration data is provided by the camera manufacturer. Additionally, PF and ZfT acquire ground truth surface correction data collected at agricultural and silvicultural research sites of TUM.

For all processing elements a backup solution is designed to ensure the processability of the real satellite data under differing, adverse conditions. The alignment, coregistration and georeferencing steps are done iteratively to refine the results.

As the camera is a pushbroom system, correct alignment of the individual image rows is essential. To achieve this, both a deep neural network and a SIFT feature detector (LOWE 2004) are used to identify tiepoints in overlapping image strips with high confidence on a sub-pixel level. The tie points and a DTM together with the attitude and orbit information provided by the satellites are used within a bundle block adjustment system to generate a first corrected, more precise set of attitude and orbit information to realign the individual image rows for corrected strips.

The image strips are then divided into blocks less than 75 km in length for further processing at the BVV. This is to ensure that earth's curvature does not impose restrictions on the 2D intermediate processing. Building centers are extracted to find a mapping to cadastral data for a first georeferencing of the image blocks. A neural network for building center extraction on aerial imagery (ROSCHLAUB et al. 2020) is currently being adapted to simulation data for our mission. The extracted centroids are fused into settlement clusters in resolutions of 40, 400 and 4.000 m. Then, a transformation from the extracted cluster centroids to the settlement cluster centroids of the cadaster is calculated (ROSCHLAUB et al. 2023) to obtain preliminary transformation parameters. After this rough transformation, the alignment can be further refined at the full 4 m resolution as coarse misalignment errors with individual buildings are now precluded.

A backup system for the coregistration of key points uses density maps of extracted and cadastral building centroids and calculates transformation parameters via cross correlation. This is a simple and stable system but due to its computational cost not preferred.

As an alternative to the above-mentioned process, a neural network that directly coregisters the individual image rows onto an already georeferenced orthoimage will be tested. This will also utilize a DTM within the coregistering chain.

4 Mission Simulator

4.1 Overview

To be able to determine the mission requirements more precisely and to verify assumptions on the performance of the overall system concerning data processing possibilities, a data simulator is being built. It is designed to assess the impact of design and part choices on the expected resulting data throughout the processing chain and generate test data. APG, ZfT and BVV also implemented testbeds for their respective focus areas. The current elements of its PF part are discussed below.

4.2 Virtual Satellite Camera

A core element of the simulation is the ability to produce artificial satellite data which resembles the expected real mission results and therefore shows the impact of design choices and parameters on the produced raw data and subsequent processing products. As the virtual satellite camera's detailed underlying methodology is part of a separate DGPF publication (LENZ & GREZA 2023), the following section will focus on its role within the whole simulator.

High resolution TrueDOPs act as a base image from which the artificial satellite images are created. The BVV provides PF with TrueDOP40 imagery from its Bayernbefliegung campaign for this purpose. For its core functionality, a virtual camera flies over the base imagery and captures it with respect to sensor specs, camera parameters, the orientation of the satellite, field of view and radiometric behavior. Its path is determined by propagated orbits that were created by APG. During the capturing process, the base image pixels are projected onto the sensor pixels and degraded through filtering and modulation transfer functions. This produces more realistic image lines than simple downsampling from the 0.4 m base GSD to the 4 m GSD of the satellite. The next iteration of the virtual satellite camera will also make use of a high resolution DTM to further improve the imaging geometry, which is especially relevant in mountainous regions as lines of sight are heavily impacted in these areas.

As there are no ground truth images available yet, the tuning of radiometric and geometric postprocessing is currently bound to qualitative assessment of the images by comparing to images of different satellite systems, i. e., Sentinel-2 (SENTINEL HUB 2023), Planet Dove (PLANET TEAM 2017), and Landsat 8 & 9 (USGS 2023). To tackle this, several radiometric and geometric calibration tests are tasked with the engineering model camera and its lens system. Their results will be used as more accurate parameters and enable a quantitative radiometric assessment of the virtual camera.

The simulated image strips are then used to test the processing chain that is laid out in chapter 3. Figure 1 shows an exemplary cutout of a virtual overpass. The most important tests for the mission design are the production of strips with differing overlap values to determine the minimum desired overlap and the introduction of tumbling, as well as attitude and position inaccuracies. These verify the constellation design and satellite subsystem requirements. In figure 1, a test with mismatching ground speed and image acquisition frequency results in a slight along-track distortion.

Fig. 1: Simulated satellite image with mismatching line rate at 4 m GSD derived from DOP40

4.3 Image Degradation

4.3.1 Optics and Sensor Degradation

An automatic processing chain must be robust against adverse conditions. To find breaking points within the system, the simulator imagery can also be further altered to reflect potential threats to the processability.

One option, which was implemented with support from Ramesse Zatti, is to add sensor noise and pixel faults that could emerge in orbit as well as simulate the effects of particles on the lens. One of the driving causes for degradation in LEO is atomic oxygen, which due to its reactive nature can erode spacecraft surfaces and create particles that settle on the sensor and lenses. Several publications on atomic oxygen damage in LEO provide modelled and measured values for various surface orientations in relation to flight direction. As it was not possible to generate a consistent model from their results, three distinctive values were chosen for our simulations. Useful values from the Long Duration Exposure Facility and the Tropical Rainfall Measuring Mission (TRMM) were taken as reference. TRMM operated during a solar maximum, resulting in high values of atomic oxygen. A total atomic oxygen fluence of $8.9 * 10^{22}$ atoms per cm² was calculated (CHEN 2001).

Value 1: With a front-facing camera, we assume that 95 % of atomic oxygen fluence results in damages. (PETERS et al. 1986)

Value 2: With a side-facing camera, we assume that 4 % of atomic oxygen fluence results in damages (BANKS et al. 2004).

Value 3: With a rear-facing camera, we assume an atomic oxygen fluence of 10^4 (CHEN 2001).

For first tests we assumed a pixel failure rate of 0.5 % per year like the TRMM experienced in LEO based on (CHEN 2001) and adapted this to the three standard camera orientations. It is to note that these 0.5 % is a combination of atomic oxygen effects as well as charged particle interference.

As expected, test results show that a rear-facing camera during the satellites' maneuver configuration is to prefer over a front-facing orientation.

Further particle sources apart from atomic oxygen are material outgassing, venting, leaks, and propellant plumes. Together with residuals from assembly and launch, contaminations and dust depositions occur on the optics, resulting in smaller transmissive capabilities of the lens system. This effect is applied to the image in figure 2. These can become a relevant element over the planned mission lifetime over five years. The impact of the string of pearls constellation configuration executing maneuvers resulting in propellant plumes have to be analyzed and modelled further to derive recommendations for camera orientation during the maneuvers. It is assumed that a trailing camera will also be favourable.

Fig. 2: Simulated satellite image including heavy degradation for system failure tests

4.3.2 Cloud Generation

A second capability of the image degradation simulator is the possibility to generate artificial clouds within the images. As parts of the image processing chain rely on tie points and ground control points derived from deep neural networks, low visibility due to high cloud coverage can result in failure of the high precision processing. To be able to find these breaking points and create more resilient models that can cope with inter alia lighter fog or partly cloudy areas, a cloud generator was implemented with support from Yifan Xu. By using Perlin noise (PERLIN 2002), fog as well as cirrus, stratus (figure 3) and cumulus clouds can be generated with differing coverage and wind orientations.

Fig. 3: Exemplary simulated satellite image containing stratus clouds

5 Outlook & Discussion

5.1 Future Data Products

As the design phase is ending, the focus of the teams shifts from satellite and mission design towards assembly, component testing and the implementation of data processing on different levels. For the latter, the project team is working with Bavarian administrative bodies to develop new application systems for the data processing levels 2, 3 and 4.

More common target applications in agriculture and silviculture are precision farming techniques like yield prediction, plant health monitoring and disease detection as well as subsidy monitoring and damage assessment.

Further, rapidly available reconnaissance data after natural disasters are of high value and are a planned product outside of the routine applications. For this, a tasked spotlight mode can be tested within the demonstrator mission. This enables an even higher acquisition frequency and the generation of DEMs, for example after landslides.

5.2 Mission outlook & Discussion

As this is a demonstrator mission, the insights gained throughout development and especially during satellite operations will set the base for a follow-up full extension mission which will cover the whole state of Bavaria with its satellites. Especially the need for a high precision AOCS creates engineering challenges for a CubeSat system. Without real data available, the demonstrator mission is the only way to verify design choices for a full extension. AOCS precision directly correlates with the number of satellites needed for the full coverage of Bavaria and therefore cost. CubeSat constellations have impressive capabilities at a low cost, but some caveats remain. Design restrictions because of their limited space can be easily seen in the size limits of feasible optics and in data rates. Even with its high-bandwidth antennas, data transfer imposes restrictions on possible image strip lengths. With its full extension, the mission will cover the whole of Bavaria but transferring significantly longer strips (e. g. also covering parts of Hesse, Thuringia, Northrine-

Westphalia, and Lower Saxony) is not possible within the revisit time in current satellite specifications. Expanding the mission and satellite design after a successful demonstration should be discussed to further expand the capabilities of the system.

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