Technische Universität Braunschweig

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planet.

Automated conStellatIon Management Of space Vehicles

Executive Summary Report - ESR

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1 Introduction

Recently, a variety of satellite constellations, some of them feature spacecraft quantities up to over a thousand of satellites, were announced. While similar concepts for large constellations already existed in the past, today's satellite constellations hardly ever feature triple-digit satellite quantities. The up today world's largest constellation operated by Planet has about 190+ Dove spacecrafts.

This trend towards considerably larger constellations originates from non-traditional design and operations of spacecraft by non-traditional space companies. This evolution in the space sector, precipitated by new players, is often referred to as "Space 4.0" or "New Space". It necessitates a rethinking of the way satellites and satellite constellations are planned, designed, and operated. The satellite cannot be considered and operated as an individual anymore, and the management of the system as a whole—with a significant increase in automation—has to come to the fore.

There are crucial qualitative challenges that arise when moving from moderately-sized groups of individual spacecraft to large-scale constellations. The consequences of this paradigm shift include higher complexity of (i) basic communication tasks and ground resources allocation, (ii) coordination and higher probability of anomalies, (iii) of mission objectives, and (iv) space situational awareness (SSA) functionalities.

New operational paradigms are needed to enable automatic, optimal task definition, and scheduling in a holistic approach. The study evaluates the fundamental challenges that arise when large constellations have to be efficiently operated and automation levels have to be increased, as well as the different automation levels (L1 basic sequential automation, L2 distributed automation, L3 adaptive automation, and L4 mission-aware automation) and their impact on mission operations.

The executive summary report summarize the results of the ASIMOV project (**A**utomated con**S**tellat**I**on **M**anagement **O**f space **V**ehicles) and depicts initial approaches and areas for developing appropriate automation strategies, classify constellations and evaluating a new market driven automated scheduling concept by the ASIMOV consortium, consisting of the Institute of Space Systems at Technical University of Braunschweig (TUBS), the Algorithms Group of the Institute of Operating Systems and Computer Networks at TUBS, and Planet Germany.

2 Overview of Conventional Satellite Operations and its Scalability

Traditionally, owning and operating a satellite was only the purview of governments or large corporations. In the 1990's and early 2000's, the "Microspace" movement, the precursor to New Space, allowed the size and price of satellites to decrease significantly such that small companies or universities could begin to launch satellites on their own. Nevertheless, building and launching these microsatellites still cost 10's of millions of dollars and they were still operated as conventional spacecraft. Even today, with the advent of the New Space paradigms, many commercial satellites can still be regarded as conventional. The defining characteristics of conventional satellites are:

- “Expensive”
- Small number of spacecraft
- Need for high system reliability (no on-orbit spare or maintainability)
- Each pass is monitored
- 24/7 operational support
- Large teams of subsystem experts
- Manual commanding (little automation)
- Single ground station
- Manufacturer and operator are two separate entities
- Classic systems engineering approach
- Documentation and configuration control

In the following sections discusses conventional spacecraft and spacecraft operations as well as their scalability and makes a comparison to new paradigms that begin to emerge as constellation sizes exceed hundreds of satellites. The paradigms shifts described here relate to both the automation and control elements of large constellations, as well as broader observations about the satellite industry compared to when using a conventional operations approach. In such classical approach each satellite added to a system requires additional operator effort since an operator’s time is split between the existing assets. As a constellation grows from single digits to double digits in number, a conventional system’s scalability is stressed and will eventually cease to function smoothly. Areas of stress - resource allocation, satellite development, commissioning, nominal operations, software and configuration, orbit management, and payload activities - are summarized in Figure 1. Addressing those type of problem areas requires a shift in operational concept that reduces the operational effort of maintaining these large, complex constellations.

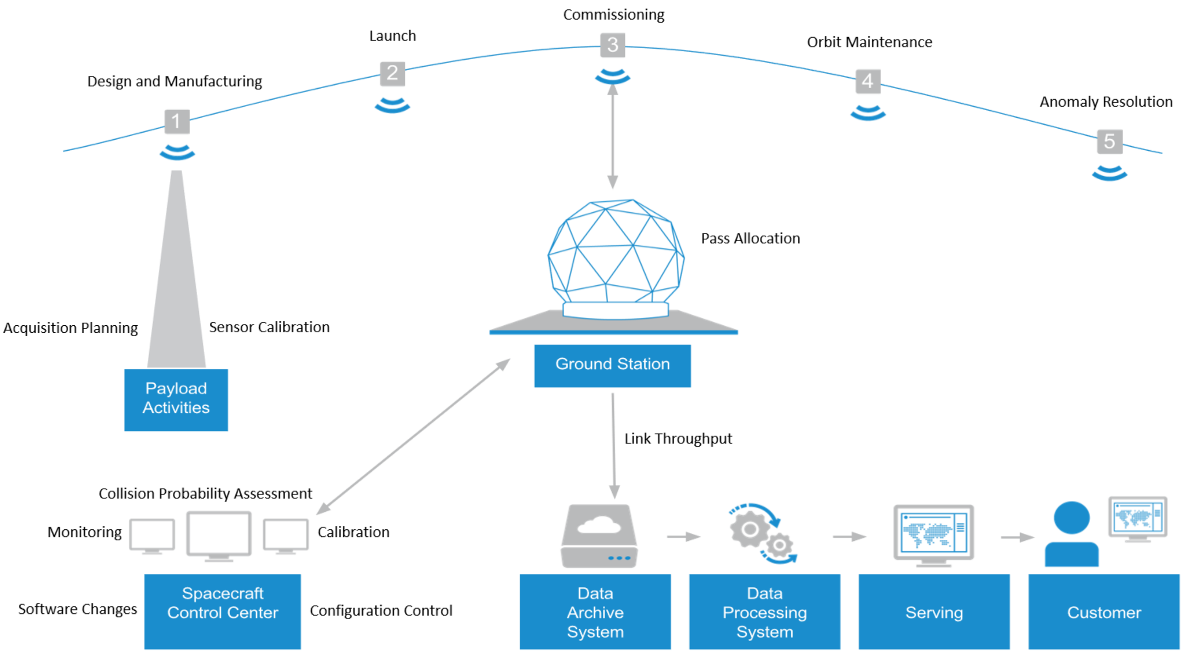

Figure 1: Weakness areas in conventional satellite operations

(1) **Satellite Design, Manufacturing** is highly specialized and costly, which means few satellites are produced at a time and manufacturing a large number of spacecraft using conventional approaches does not scale well. Paradigms change from:

- **Subsystem Redundancy → Satellite Redundancy** (e.g. satellites produced quicker and cheaper. It is now possible to provide on-orbit redundancy.).
- **Single Mission → Multi-Mission** (e.g. RapidEye, Dove, and SkyBox systems together provide medium and high resolution EO datasets.).
- **Long Lifetime Satellites → Short Lifetime Satellites** (e.g. Replenishing satellites in a constellation more frequently enables a long duration mission with less dependence on highly reliable single satellites.).
- **Large Satellite Bus → Small or CubeSat Bus**: (e.g. smaller satellites result in better access to space by using secondary launch opportunities and reduced single unit cost).
- **Separation of Manufacturing and Operations → Co-location of Manufacturing and Operations** (e.g. performing both manufacturing and operations within the same organization allows for this feedback loop to be better closed and provides smoother design iterations.).

(2) **Launch**

- **Single Primary Launch → Multiple Secondary Launches** (e.g. CubeSat, or microsat form factors provides a cost savings and easier access to space.).

(3) **Commissioning** hands over the s/c system from the satellite manufacturer to the satellite owners/operators and teaches them how to operate their new satellite system. Performing commissioning activities for each spacecraft is necessary before it can enter operations and does not scale well.

- **Complex Manual LEOP and Commissioning → Automated LEOP and Commissioning:** (e.g. automated commissioning becomes the norm, manual intervention is only required to initiate processes and solve anomalies.).

(4) **Orbit Management and Collision Avoidance** on a conventional satellite, requires calculations for the current and desired orbital parameters and then an assessment of the ΔV required to change the orbital parameters. Conventionally, orbit maneuvers require a great deal of manual preparation and coordination. Increasing the number of satellites increases the overall amount of preparation, coordination, review, and operator time.

- **In-house Collision Probability Assessment → External Collision Probability Assessment**: (e.g. as the number of satellites grows, automation systems must be developed to perform some of this assessment. Several commercial offerings are available to perform this service.).

(5) **Nominal Operations, Monitoring, and Anomaly Handling** ensures safe satellite operations and availability. Satellite telemetry and log files are regularly reviewed where systems for automated screening of log files and telemetry against thresholds are commonly employed. Manual telemetry review is still frequently needed and performed. For large constellations inspecting one spacecraft at a time and conventional approaches for anomaly resolution are no longer feasible, so techniques must be developed for easier comparison and data presentation.

- **Manual Telemetry Review and Alerting → Automated Telemetry Review and Alerting:** (e.g. automated telemetry checks, typically based on limit thresholds, must be used).
- **Automated Telemetry Alerting → Automated Anomaly Reaction**: (e.g. Well-characterized anomalies can be resolved in automated fashion to avoid human-in-the-loop telecommanding of critical systems.).
- **Subsystem Specialized Operators → Small Number of Generalized Operators:** (e.g. bulk of operations to be handled by a small team of generalists rather than requiring subsystem specialists to be available for around the clock operations.).
- **Multiple Satellites → One System:** (e.g. constellation must be considered holistically and metrics must be defined that allow for the overall system health to be assessed.).

(6) **Resource Allocation - Planning and Scheduling** With a low number of satellites various factors and constraints are accounted (e.g. for EO: cloud forecast, previous acquisition history, and payload access to sensing site, satellite resources etc.) For small constellations in the right orbital configuration, it is possible to

perform simple pass allocation for telemetry, tracking, and control. The latency of satellite data availability is a direct consequence of using a single ground station. Resource allocation doesn't scale well with increasing no. of s/c. Sharing antenna's resources between satellites becomes more complex to the point when manual pass scheduling or simple pass allocation techniques (i.e. used when no competition exits) are no longer feasible.

- **One ground station → Multiple ground stations:** (e.g. constellations are taking advantage of distributed networks of ground stations and perform deconfliction activities to ensure performance.).
- **Limited Resources → "Unlimited" Resources:** (e.g. modern spacecraft designs take advantage of powerful consumer electronics improvements in solid state drive storage and processing power.).
- **Selective Payload Coverage → Complete Payload Coverage:** (e.g. concept of operations for payload coverage can be changed: rather than focusing on specific high priority areas of interest, global coverage.).

3 Use-Case Analysis Galileo and Planet

The system investigated in the use case analyses are the European global satellite navigation system called GALILEO, which is expressly designed for civil use and as Planet operates the largest fleet of Earth Observation satellites in the world the three separate satellite constellations of Planet:

1. RapidEye: architected following conventional aerospace practices
2. Skysat: combining both agile and conventional operations
3. Dove: architected following agile aerospace philosophy

The summary of those Use Case Analyses Constellations and their assessed levels of automation are shown in Table 1. Following nomenclature was used:

- **Manual** - little or no automation is used in this process.
- **Semi-automatic** - parts of the process have been automated, but operator intervention in the process is required.
- **Automatic** - the majority of this process has been automated. Operator intervention is required only in the case of anomalies or to initiate automated processes.

Table 1: Use Case Analyses Automation Level of Galileo and Planet's Constellations

Automation Topic	Galileo	RapidEye	SkySat	Doves
LEOP & Commissioning	Manual	Manual	Semi-automatic	Automatic
Constellation Tasking	Semi-automatic	Semi-automatic	Semi-automatic	Automatic
Software Updates	Manual	Manual	Semi-automatic	Semi-automatic
Configuration Changes	Manual	Manual	Semi-automatic	Semi-automatic
Data Downloads	Automatic	Automatic	Automatic	Automatic
Telemetry & Log Monitoring	Semi-automatic	Semi-automatic	Semi-automatic	Semi-automatic
Anomaly Handling	Semi-Auto (FDIR) Manual	Manual	Semi-automatic	Semi-automatic
Orbit Control and Maintenance	Manual	Manual	Manual	Automatic
Collision Avoidance	Manual	Manual	Manual	Automatic
Calibration & Validation	Manual	Semi-automatic	Semi-automatic	Semi-automatic
Ground Station(s) Tasking	Semi-automatic	Semi-automatic	Semi-automatic	Automatic

The current way Galileo is operated supports the planned operation of up to fifty satellites but does not scale well for growing number of spacecraft and is certainly not suitable to operate "mega constellations". A classification system for categorizing constellations, which takes into account the workload related to operational tasks, as well as the scalability of these tasks can be used to identify and prioritize operational tasks to be automated and is presented in detail in D2 of this study. New capabilities related to Galileo second generation such as inter-satellite link should be taken into account for future developments. Such technology changes the architecture of information processing and thus extends the achievable scalability levels and the applicable automation techniques. Planet currently operates the world's largest commercial satellite constellation and is at the forefront of satellite automation. However, control of the RapidEye, SkySat and Dove constellations is not fully automatic: small teams of engineers work full-time to ensure the health, safety and nominal operations of the spacecraft. Further research and development will be required to increase the level of automation across the fleets and going further to autonomous systems.

The most problematic and time consuming areas in s/c operations identified during the Use-Case-Analyses are either health monitoring and anomaly detection or scheduling problems. The following chapters will lay focus on a solution for one of those problems and to be implemented in a proof-of-concepts (PoC).

4 Problem: Communication Bottlenecks

One of the identified shifts in the paradigms of the New Space area, is the increase in data that a satellite constellation will produce. Having an Earth observation constellation in mind, the amount of data will increase not only because of launching large constellations, but also due to technology improvements of the sensors in terms of quality and quantity. It is likely that the amount of data will exceed the bandwidth and/or processing capabilities. Of course, there are several possible counter-measures.

- Increase number of ground stations or the usage of more advanced communication technique to increase the bandwidth.
- On-board pre-processing of the data (e.g. cloud detection algorithms to potentially eliminate images on board the satellite directly)
- Distribute and share ground station networks (constellations with peak performance rates are compensated by idling systems)
- Inter-satellite communication (which relaxes the communication constraints)

Sharing or adding ground stations as well as relaxing the communication constraints by inter-satellite communication can help for some time but also doesn't scale very well. The counter measures still leaves the system with a scheduling problem. With a larger network and inter-satellite communication the difficulty of finding a valid schedules also drastically increases. While one could theoretically still have enough bandwidth, the scheduling algorithm might not be able to find suitable schedules in time to utilize it. This raises the question when the system is no longer able to download everything, and the classic scheduling algorithms fail how should downlink time and ground station passes be scheduled?
As a potential solution, a distributed auction-based scheduling strategy where economy-based behaviours distribute the limited resources that the gain (valuable data) is maximized, is investigated. For example, the ground stations can act as competing (data-) reseller (see Figure 2) or the satellites could bid for time windows. This approach raises

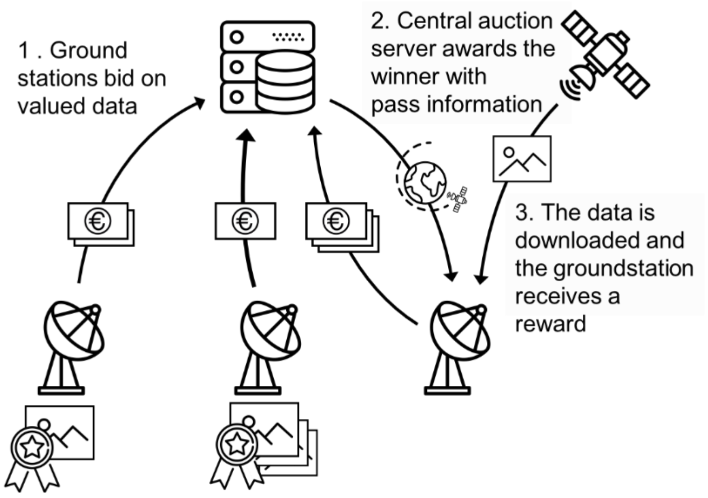

Figure 2: A possible approach for the auction system of the data market.

some general questions that have to be addressed and evaluated for an auction-based scheduling system:

- What are the goods that are traded?
  - Either the data on the satellites, communication slots with the ground stations or a combination of both.
- Who are the actors? Who buys what from whom?
  - Satellites buy communication slots and ground stations bid for data.
- When does a bidding process (auction) start? Every time a satellite has ground contact and transfers meta data?
- What does the meta data contain? How and when is it distributed?
  - The meta data can be highly application specific, however, it will contain information to assess the value of the associated data.
  - Under the assumption that metadata is small, an inter satellite communication network is a convenient solution to distribute the metadata (if ISL are available).
- When does an auction conclude? How long does it take? How and when are the buyers/sellers notified?
- What are the bidding strategies of the buyers? Do they differ between different buyers? Why do ground stations bid different amounts for the same piece of data?
- Is the winning bidder (ground station) committed to download the data? Can the buyer forego the bought data in favour of a better deal that was not known until later? If yes, what happens with the data? Is it offered again?
- Who decides how valuable a certain piece of data is? Decided or estimated by the satellite? In the latter case, estimated again after download? How is value assessed at all? Is a value of say 100 units low or height? Assessment based on history?

- Do satellites offer all of their data as a package or is it split up in smaller units? Can smaller units lead to conflicts because they are bought by different ground stations? Can the bidder make its bid dependent on bids for other data?

4.1 Data Market Scheduling Algorithm

The data market is a concept for a bidding-based Ground Stations as a service approach for competing parties and for a scheduling algorithm in the event that not all data can be downloaded due to high competition for ground station contacts. The objective of the algorithm is to maximize the value of the downloaded data. Three algorithms have been implemented as a comparison: A simple greedy algorithm that mimics human behaviour, a naïve data market algorithm that has been a simple prototype but only implements parts of the data market idea, and the dynamic data market algorithm which is the final algorithm.

- **Greedy:** Schedules the best contact within a specific time window. Repeat until no further contacts can be scheduled (see slides of the final presentation for an example).
  - Absolute: Choose the contact with the highest absolute value.
  - Relative: Choose the contact with best ratio (value/length).
- **Naïve Data Market:** A simpler version of the data market that is somewhere between greedy and the Dynamic Data Market. It shares some ideas but is less dynamic than the real data market. It is not able to use partial contacts in its current implementation, so it has a handicap.
- **Dynamic Data Market:** The data market where satellites bid on contact windows. It has higher scalability and a lower computational complexity than the naïve data market. In particular, it can be better distributed. This is a major selling point of the dynamic data market: The bidding can be done by the satellite operators according to different strategies (which they want to run on their own computers).
  - Basic: No adaptions.
  - Modified: Closer contact windows get a higher rating.

Another objective of the data market concept is the sharing of a ground station network even among competing systems, i.e., ground stations as an (independent) service. Allowing the systems to have their own (secret) bidding algorithms/strategies in order to fulfil their needs with minimum costs is a fundamental part of the data market concept. Only the dynamic data market allows this functionality. However, we do not have a reasonable way to evaluate this behaviour such that we limit ourselves to evaluating the general scheduling performance.

5 Simulation Strategy and Results

The main objective of the PoC simulation is to demonstrate the generic effects of increasing constellation size, advancing satellite communication and progressing automation level. As a consequence, the demonstration will not aim at a fine-grained simulation of specific satellite architectures; for easier reference, however, many of the basic parameters will be chosen in accordance to real reference constellations, which are then tested for enhanced size, communication and automation levels. With the following definition of the constellation parameters, data parameters and the description of ground stations four scenarios were defined and evaluated:

- Simulation scenario 1: 400 Satellites, 5 ground stations
- Simulation scenario 2:1080 Satellites, 6 ground stations
- Simulation scenario 3:Galileo, 2 ground stations
- Simulation scenario 4:40 Satellites in LEO, 6 ground stations

Except the Galileo instance, all instances require to fix the schedule 3 hours ahead and can look 9 hours into the future. The Galileo instance can look 24 hours into the future. The storage on each satellite is 10,000 download seconds.

Units:

- Rates are measured in percent, for example downloaded data value of all data value.
- Time is measured in seconds.
- Data Volume is measured in seconds needed for download.
- Value is an imaginary unit. It has no dependency to other units.

To give an overview of the simulation results and the performance of the different Data Market strategies simulation scenarios 1, 2 and 4 are shown and compared to each other because the use the same initial condition with focus on the average value and data rate per satellite.

For scenario 1 no performance differences in respect to data rate and value can be observed. With increasing constellation size for the other scenarios the dynamic and modified dynamic algorithm perform more or less the same and the performance is significantly better than the simpler algorithmic concepts.

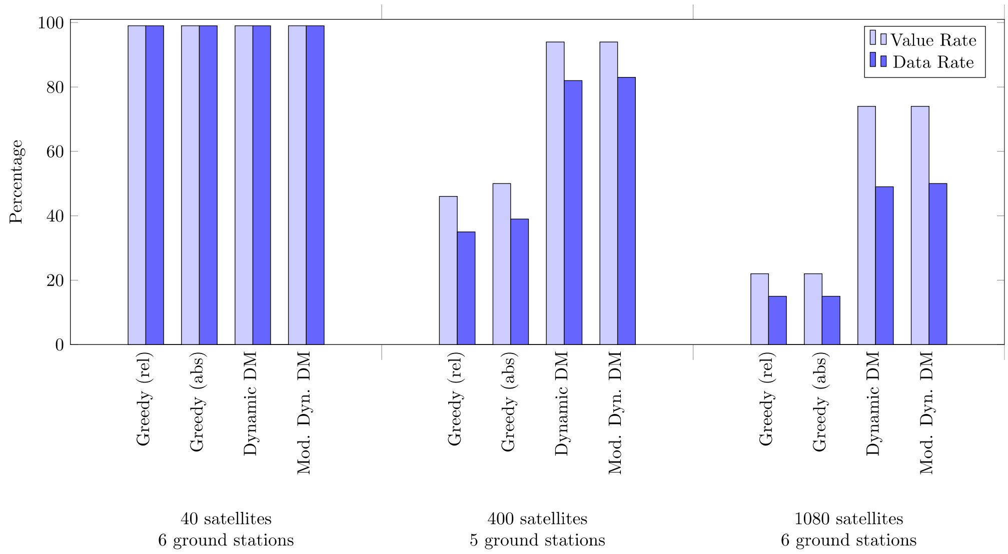

Figure 3: Bar chart comparison the different algorithms for the three simulation scenarios.

Table 2: Date and Value Rate of all algorithms for simulation scenario 1.

40 satellites, 6 ground stations	*Value Rate*	*Data Rate*
Greedy (relative)	99%	99%
Greedy (absolute)	99%	99%
Naïve Data Market	99%	99%
Dynamic Data Marked	99%	99%
Modified Dynamic Data Market	99%	99%

Table 3: Date and Value Rate of all algorithms for simulation scenario 2.

400 satellites, 5 ground stations	*Value Rate*	*Data Rate*
Greedy (relative)	46%	35%
Greedy (absolute)	50%	39%
Dynamic Data Marked	94%	82%
Modified Dynamic Data Market	94%	83%

Table 4: Date and Value Rate of all algorithms for simulation scenario 4.

1080 satellites, 6 ground stations	*Value Rate*	*Data Rate*
Greedy (relative)	22%	15%
Greedy (absolute)	22%	15%
Dynamic Data Marked	74%	49%
Modified Dynamic Data Market	74%	50%

To differentiate between a simulated environment used for the scheduling algorithm and a live environment, which resembles the real world in the proof-of-concept a feedback mode with different level of fidelity in the orbit prediction is used. The feedback simulations confirms the general behaviour of the data market and shows that scenario 2 with 400 satellites and 5 ground stations puts much more pressure on the algorithms and the limiting factor is the availability of the ground stations. There are so many contact possibilities now that it is really necessary to choose wisely in order to maximize the effort. In scenario 3, which features 1080 satellites inspired by the One Web constellation concept the main constraining parameter are again the ground stations and overall contact time they can provide. All satellites manage to have frequent contacts with a ground station, see Figure 4. There is a variance in the number of contacts, but no spacecraft is left far behind. The scaling capabilities of the data market can be shown and the ground station utilization (data rate and value) is slightly better (Figure 5). With one more ground station than in scenario 2 but more than double the amount of s/c, the communication gap and contact frequency is not linear decreasing. In average a contact is scheduled every 30 to 40 hours and the maximum gap is between three to four days. (More results can be found in D6)

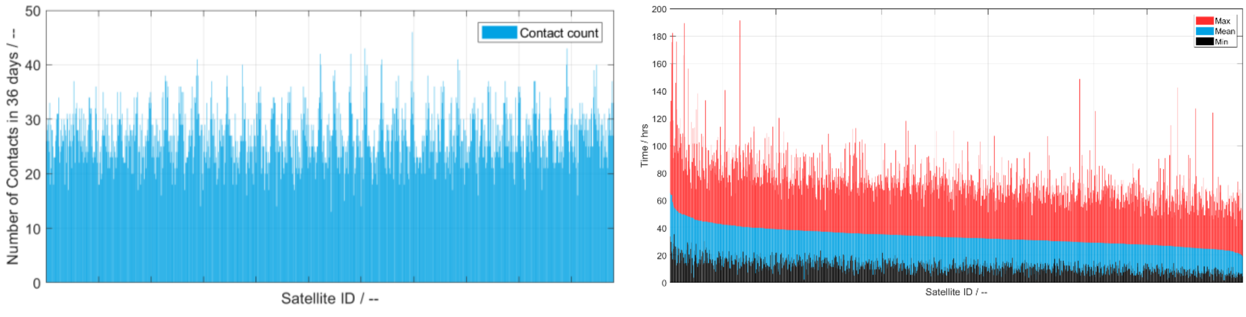

Figure 4: Scenario-3 left: Contact frequency per s/c right: Contact gap per s/c.

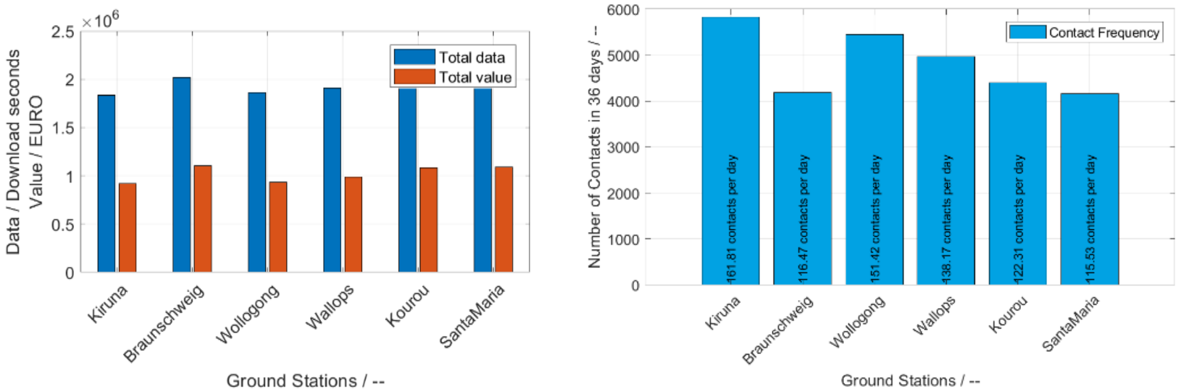

Figure 5: Scenario-3: left: utilization of the 6 ground stations; right: total number of contacts and average frequency per each ground station.

6 Conclusion

Pass allocation was identified as one of the challenges of future spacecraft operations. The paradigm shift from one or few satellites to many satellites in a large constellation, requires an operational concept on system level which uses higher levels of automation to command the individual satellite and deal with anomalies, etc.
The proof-of-concept simulation results implement a simplified model for the pass allocation scheduling problem. The general idea of the simulation scenarios is to increase the number of satellites and at the same time keep the number of ground station antennas constant. This eventually creates a bottleneck on the availability of the antennas on ground. The result of the pass prediction result in many concurrent possible download windows for many satellites. The challenge for the algorithm is to solve this concurrency problem and select an appropriate schedule, which is then applied to the constellation. It was decided to model a dynamic data market economy in order to solve the scheduling problem. This is essentially a self-organizing system, which can also re-adapt to changes in the constellation system (such as the failure of a satellite in the constellation or the unavailability of a ground station because of maintenance).
The simulation result show that a data market implementation can successfully and continuously define the schedule for a large constellation (of up to 1080 satellites). The performance is significantly higher compared to a greedy, human-operator inspired reference case.
For future work several aspects can be further investigated. The algorithm can be further tuned with a systematic parameter study that identifies general valid as well as the system specific parameters. The momentary simplifying assumptions can be addressed and a more "realistic" integrated data market with information updated on s/c contact could be implemented. In addition different concepts of operations (e.g. PL & TT&C scheduled together on same ground station (parallel) or TT&C and PL scheduled separate two parallel data markets). Also the topic of inter-satellite link (ILS) came up several times during the project but couldn't be investigated further. Inter satellite links will create dynamic network connections (between the satellites in the constellation) which need to be considered in a simulation. This on the one hand will add another level of complexity but on the other hand can also significantly improve the performance of the system. So in future especially the impact of ILS on Data Market needs to be investigated as well as the robustness of data market in terms of anomaly reaction.