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Reducing Data Latency with Inter-Satellite Links in LEO Constellations: Trade-off Analysis and Impact on Concept of Operations

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Abstract

Information on its own has a value but equally the point in time when that information is received is also an important consideration. Data latency, the time needed to perform the measurement with the satellite's payload and deliver the actionable information to the customer, is a key design decision for ensuring the customer's needs are met whilst ensuring the mission's costs are viable. The conventional approach in satellite missions has been to wait until the next booked ground station is overflown, transmitting the data to the ground station and subsequently transferring the data to the data processing center where the derived products are generated. Each of these steps take time and, in their sum, contribute to the total duration of the data latency. When designing or assessing concepts for monitoring activities globally on the Earth with LEO satellite constellations, the constellation itself offers new ways of reducing the data latency. In addition to the existing data transmission service from LEO via GEO to the ground, the data latency can also be reduced either by employing inter-satellite links or edge computing. In this paper we compare the approaches of using i) a ground station network, ii) optical inter-satellite links and iii) edge computing to affect the data latency and compare their use on the annual operational expenditure for the mission.

Our analysis shows that incorporating inter-satellite links reduces the data latency by a factor of 2 when compared to constellations solely relying on a ground station network. Whilst onboard processing offers advantages, such as reducing the amount of data that has to be downlinked, it does not reduce the data latency. The interference of the optical link's performance due to sunlight is not considered to have an operational constraint or significant impact on the data latency. Inter-satellite links importantly allow the locations of ground stations to be placed where desired. To achieve an equivalent data latency without inter-satellite links and solely a ground station network requires a factor of 5 more OPEX, i.e. that saving can be used to finance the CAPEX of the inter-satellite links or compute the break-even point. Alternatively, a constellation using solely a ground station network achieves a 90th percentile data latency that is slower by a factor of nearly 6 using an equivalent OPEX that constellations with inter-satellite links require.

Keywords: Satellite Constellations, Data Latency, Inter-satellite Links

Nomenclature

t	Time	*Subscripts:*	
c	Cost	*sat*	Satellite

Acronyms/Abbreviations

CAPEX (Capital Expenditure), Ground Station (GS), Inter-Satellite Link (ISL), Low Earth Orbit (LEO), NASA's General Mission Analysis Tool (GMAT), Operational Expenditure (OPEX), Payload measurement completion to acquisition of signal at the ground station (PM2AOS)

1. Introduction

When designing, analyzing or assessing concepts for monitoring activities globally on the Earth with LEO satellite constellations, the timely delivery of the derived information to the target customer and its associated value has to be assessed. This is a key design decision for ensuring a business model is achieved or that the budget envelope for the mission's capital expenditure (CAPEX) and annual operational expenditure (OPEX) is met. Furthermore, it is a vital metric when comparing the performance and cost-benefit analysis of a proposed LEO constellation with competing non-space monitoring solutions.

Information on its own has a value but equally the point in time when that information is received is also an important consideration. Some customers may be willing to pay more if they can receive information in a timely fashion that allows them in turn to take appropriate action. Other customers may be more price sensitive and wish to judge what the timeliness of the information is worth to them compared to the price they are asked to pay. For some customers timeliness is simply not an issue as long as they receive the information at some point in time. Therefore, the data latency for the information derived from the monitoring data by a LEO satellite constellation has to be assessed, as well as what costs are required to achieve a particular data latency.

In this paper, data latency is defined as the time needed to perform the measurement with the satellite's payload and deliver the actionable information to the customer. As Fig. 1 shows, once the data has been acquired the conventional approach in satellite missions (Option 1) is to wait until the next available or booked ground station is overflown, transmit the data to the ground station and subsequently transfer the data to data center where the data is then processed. The derived information or products then have to be made available to the customer. Each of these steps takes time and, in their sum, contribute to the total duration of the data latency.

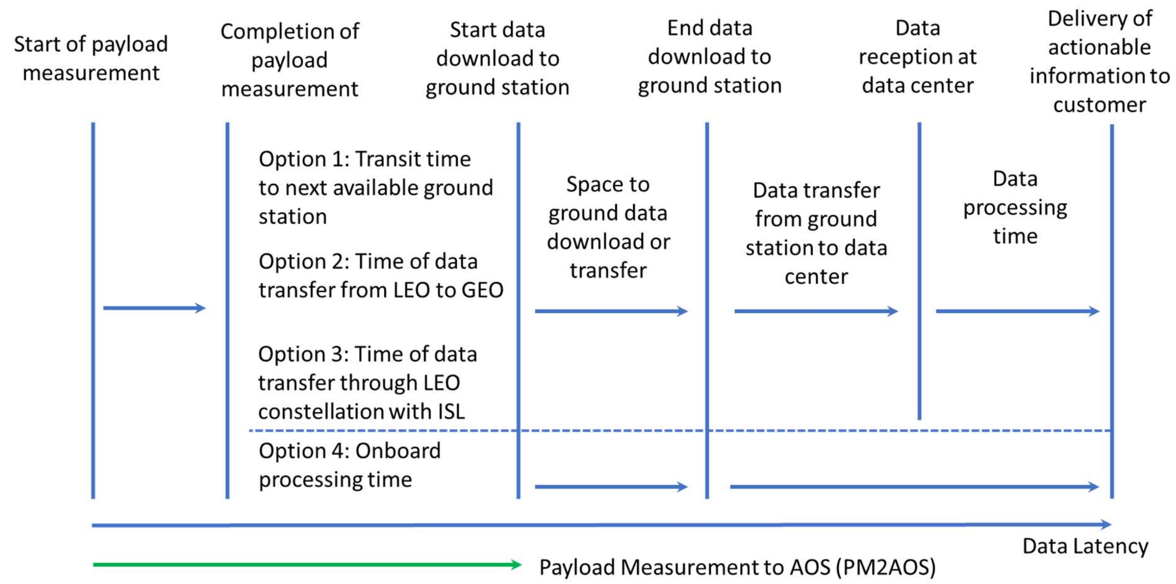

Fig. 1: Definition of data latency in this paper

In LEO monitoring missions a method for reducing the data latency is to transmit the data from the LEO satellite up to a GEO satellite, which given its synchronicity with the Earth's surface is able to transmit the data immediately to the ground (Option 2). An example of such a data transmission service from LEO via GEO to the ground is Inmarsat's and Addvalue Innovation's Inter-satellite Data Relay System (IDRS) service [1].

A current trend in LEO constellations for satellite communications is the use of inter-satellite links (Option 3). These allow data to be transmitted directly between satellites in space and promise to significantly reduce the transit time to the next available ground station for missions performing global monitoring. There are some operational considerations such as the time needed to establish the link between the satellites, the data rate influencing the total transmission time and the data buffering at the receiving satellite's onboard data handling system, as well as the propagation of the data transferring through the LEO constellation. A further operational constraint could be posed, in the case of optical inter-satellite links, by the sun shining directly into the optical head of the inter-satellite link and thus interfering or not permitting the link to be established.

With the growing computing power and increasing affordability of onboard computers, a further option is to perform some or all of the data processing directly onboard the satellite with additional onboard computers. This form of edge computing (Option 4) allows the transit time to the next available ground station to be used effectively whilst allowing ground station booking costs to be optimized. A further benefit may be that less data has to be transmitted as the derived information, such as coordinates of a location on the Earth, can involve less data than the raw data itself.

In this paper we aim to compare the three approaches of using i) a ground station network, ii) optical inter-satellite links and iii) edge computing to affect the data latency and compare their use on the annual OPEX costs for the mission. By quantifying and comparing these three approaches we offer a trade-off comparison of the data latency that can be achieved, including each of their operational constraints, for a given price.

2. Satellite constellations and inter-satellite links

Several LEO satellite constellations are considered in this paper. A technology we consider is the use of optical inter-satellite links where at least two satellites have to be in the direct line of sight of each other to be able to establish a connection. Walker constellations define circular orbits of satellites on different equally distributed planes around Earth with the same inclination. On each plane an equal number of satellites is placed, which are also equally distributed over the circular orbit. In order to establish a connection between the satellites within one plane of a Walker constellation, the altitude and number of satellites are the crucial parameters. Fig. 2 displays various orbit altitudes and numbers of satellites per plane. To be able to establish a direct line of sight between two satellites of one plane and reduce atmospheric disturbances, at least eight satellites per plane and an orbit altitude of 600 km is required.

Table 1 shows the considered satellite constellations used in our analysis. Each constellation consists of eight satellites per plane in order to connect the satellites as a ring within a single orbital plane. These type of inter-satellite links are called intra-plane satellite links in [2]. Furthermore, if links are possible between two satellites of different planes, e.g. the satellites are close enough to have a direct line of sight which is not obstructed by Earth, then so-called inter-plane inter-satellite links can be established. These inter-plane inter-satellite links have a higher complexity due to the relative movement of the two satellites to each other. This results in high requirements for the use of optical inter-satellite links, e.g. pointing accuracy and angular velocities of the laser terminals. Using radio frequency technology for the inter-plane links reduces the complexity significantly but, of course, the possible data rate between the two satellites will decrease as well.

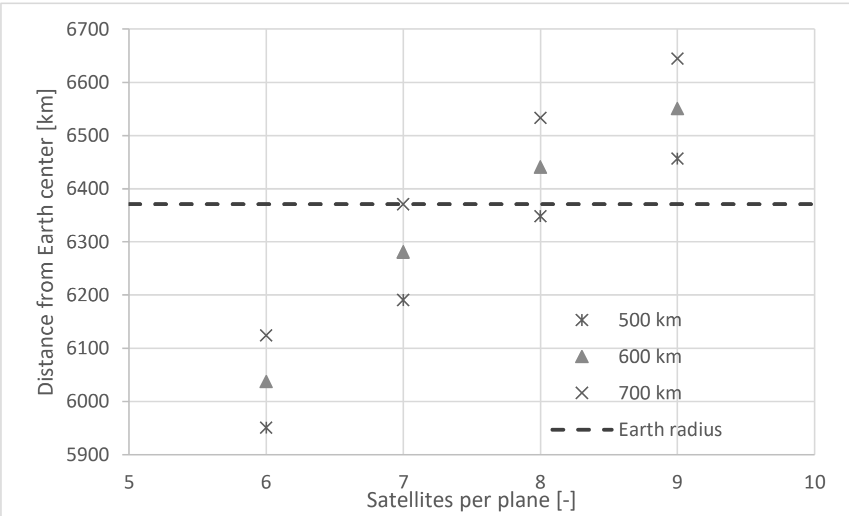

Fig. 2: At least eight satellites per plane and an orbital altitude of 600km are required to be able to establish direct line of sight between two satellites in one plane

Table 1: Selected LEO satellite constellations for this paper

Satellite constellation	Inclination [deg]	Number of satellites [-]	Number of planes [-]	Orbit altitude [km]	Comment
Walker 98:24|3|1 700	98.0	24	3	700	Used as baseline
Walker 98:40|5|1 700	98.0	40	5	700	
Walker 98:24|3|1 600	98.0	24	3	600	

3. Ground station network and area of interests

Fig. 3 gives an overview of the chosen ground stations. The locations of the ground stations are selected to achieve a worldwide coverage and an equal distribution across all world regions. The coordinates of the ground stations are taken from [3] except the one on Papeete, which is a Telemetry, Tracking and Command Station site for Galileo. Due to the high inclination angle of the considered orbits, ground stations nearer the poles have more contacts with the satellites. Table 2 gives an overview of the positions of the used ground stations.

Fig. 3 shows the considered areas of interest as well. These areas are example locations, which could be of interest for regular monitoring from LEO. For example, the areas of interest in Russia and Australia are where wildfires occurred frequently over the past years. Table 3 summarizes the coordinates of the areas of interest considered in this paper.

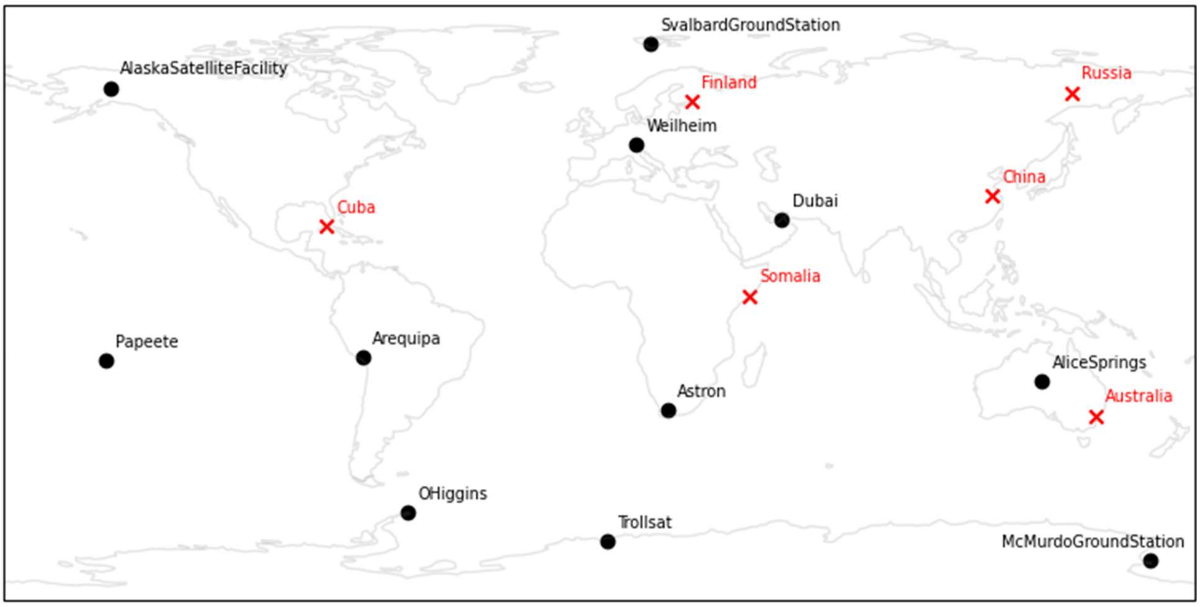

Fig. 3: Selected ground stations (black points) and areas of interest (red crosses)

Table 2: Coordinates of selected ground stations

Ground station name	Longitude [deg]	Latitude [deg]
Alaska Satellite Facility	-147.85	64.86
Alice Springs	133.88	-23.7
Arequipa	-71.54	-16.41
Astron	20.81	-32.38
Dubai	55.27	25.2
McMurdo Ground Station	166.69	-77.81
O'Higgins	-57.9	-63.32
Papeete	-149.44	-17.51
Svalbard Ground Station	15.39	78.22
Trollsat	2.32	-72.1
Weilheim	11.14	47.84

Table 3: Coordinates of areas of interest

Areas of interest name	Longitude [deg]	Latitude [deg]
Finland	27.80	60.79
Somalia	45.34	2.04
China	118.76	32.33
Cuba	-82.38	23.13
Russia	142.79	63.46
Australia	150.16	-34.15

4. Modelling

4.1 Orbit simulation

To simulate the different satellite constellations, NASA's General Mission Analysis Tool (GMAT) was used [4]. Fig. 4 shows an example of the provided 3D view in GMAT with different defined planes of satellites. The simulation settings were kept simple to reduce computational time for the different studies, for example, the gravitational force model considers Earth as a point mass when propagating the satellites' orbits and the satellites are assumed to be nadir pointing.

The selected ground stations and areas of interest are included in the GMAT simulations. GMAT provides the possibility to define a minimum elevation angle above the horizon, for which the satellites can be seen by the ground stations. This angle is set to 7° for the simulations. The areas of interest are observed by the satellite. Instead of modelling the field of view of the payload of the satellite, the areas of interest are modelled as ground stations in GMAT as well and a minimum elevation angle is set to 60°. This simplifies the simulation setup.

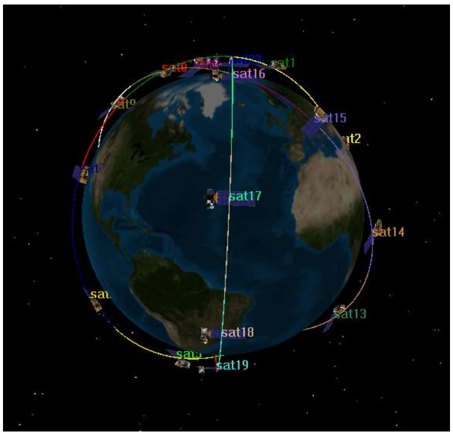

Fig. 4: Orbit simulation using NASA's General Mission Analysis Tool (GMAT)

4.2 Inter-satellite links

The modelling of the inter-satellite links uses the results from the GMAT simulations. A duration of one week is computed for which the X, Y and Z coordinates of each satellite with respect to the Earth's center are calculated. These locations are used to calculate the inter-satellite links using vector calculations. Fig. 5 illustrates simply the inter-satellite links with three orbital planes. The satellites are depicted as black dots and the inter-satellite links are illustrated as red lines. The process of data transfer after a payload measurement over an area of interest to a ground station via the inter-satellite links is explained in Fig. 1. and it can also be described by the following formula:

$$t_{PM2AOS,\ ISL} = t_{sat0,\ payload\ data\ aquisition} + \sum_{i=0}^{n} t_{establish\ ISL\ sat\_i<->s\ \ \_i+1} + t_{data\ transfer\ ISL\ sat\_i<->sat\_i+1} + t_{sat\_n\ to\ reac\ \ next\ GS} \tag{1}$$

In the simulation this behavior is mimicked by a satellite passing an area of interest. Afterwards the following steps are executed:

1. Perform payload data acquisition
2. Set the point where the satellite has completed acquiring the data
3. Check if a satellite is in the defined field of view, e.g. for inter-plane or intra-plane inter-satellite links
4. Check if the satellite is in range and the direct line of sight is not blocked by the Earth and atmosphere
5. Check if inter-satellite link is possible for the entire assumed required link duration
6. Establish the link and transfer the data
7. Permit data buffering on the satellite that has received the data and mark as having received data
8. Check if the satellite has reached the field of view of the ground station. If yes, then the simulation is stopped.
9. If not, then repeat from step 3 with all marked satellites.

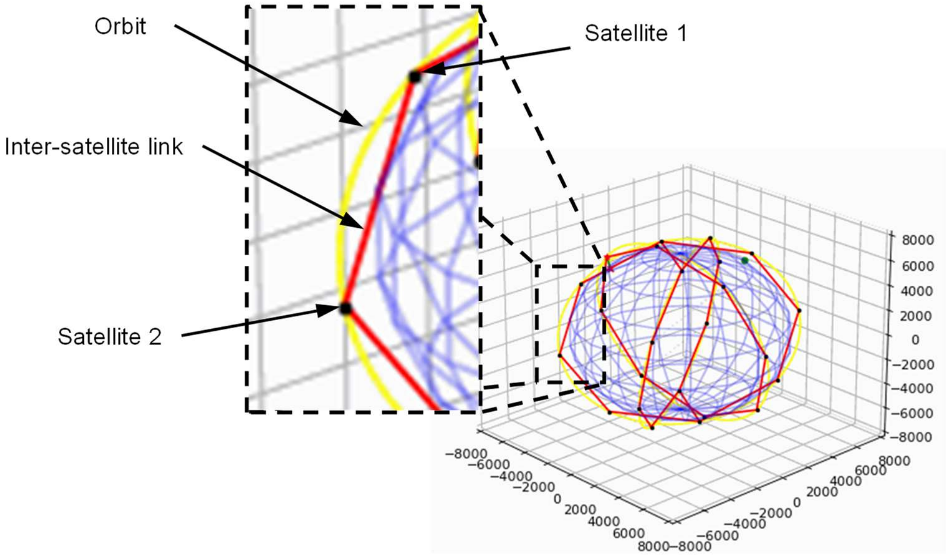

Fig. 5: Illustration of the inter-satellite link modelling

So far, we have not specified whether the considered inter-satellite links are based on optical or radio frequency technology. Optical inter-satellite links offer the possibility of very high data rates in the range of Gigabits per second. The technology is quite complex though and to establish a link between two satellites requires a high pointing accuracy. An optical inter-satellite link can also be disturbed by the sun. If the sunlight is parallel or shining directly into the optical head of the laser link, then the link cannot be established. For this reason we investigated how frequently the sun could possibly interfere with the optical links and whether unavailable links due to sun blinding might impact the resulting data latency. Fig. 6 shows the analysis of how often all possible connections between two arbitrary satellites of the considered constellations are disturbed by direct sunlight over the course of one year. A connection is considered to be disturbed if the connection vector and the sunlight vector lie within a 10-degree cone. The 90th, 95th and 99th percentile are displayed. We find that 1% of all connections are disturbed in the worst-case scenario up to 30% of the time during one week at least two to three times a year. 90% of all connections are only disturbed twice per year for 2-3 weeks up to 3% of the week's duration. Therefore, we conclude the disturbance caused by sunlight does not meaningfully impact the data transfer and in turn the data latency.

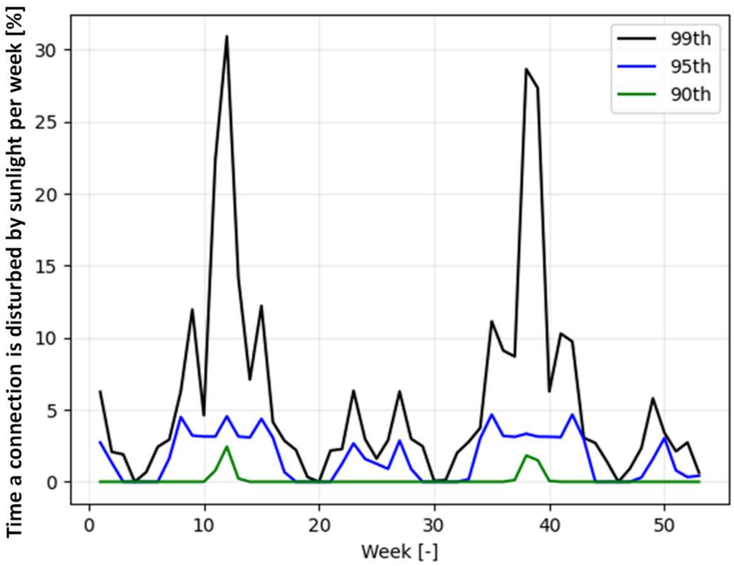

Fig. 6: Disturbance due to sunlight of the inter-satellite link connections

4.3 Parameters

Several parameters are considered in relation of the assessment of the data latency from space to ground as introduced in Fig. 1 and are explained in the following.

4.3.1 Payload measurement and data processing duration

The duration of a measurement of a given payload can be very short, e.g. if an optical image of the Earth's surface is taken, but could also take a several minutes for more complex instruments such as for a SAR payload. Only after finishing the measurement can the result be processed or prepared for the next step.

4.3.2 Required inter-satellite link connection time

An inter-satellite link connection consists of various steps. First the connection between two satellites has to be established, which is a more complex task for optical links than for radio frequency links. Furthermore, after establishing a link the data has to be transferred, which takes time depending on the possible data rate and the amount of data to be transferred.

4.3.3 Required time for onboard data buffering

A satellite receiving data via an inter-satellite link requires a certain time for buffering, processing and preparing the data for the next link to another satellite.

4.3.4 Onboard processing

One of the considered approaches for reducing data latency is to use additional onboard computers for processing the payload measurement data. Depending of the type of measurement data and datasets this could take a significant amount of time.

4.3.5 Required ground station contact time

To be able to download the desired data from a satellite to the ground, the contact duration between a satellite and a ground station has to be long enough. This also depends on the used technology and frequency bands for the transmission. With an optical space to ground link a large amount of data can be transferred but such a connection is highly dependent on the given weather conditions. The possible amount of data to be downlinked with a conventional radio frequency space to ground link is much smaller compared to an optical link but the reliability to receive the data from space is higher.

4.4 Cost model

The used operational cost model is based on the number of contacts established with each ground station, the duration of each contact and an assumed price per minute of contact.

$$OPEX\ per\ year = \sum_{i=1}^{number\ of\ contacts} t_{i\ contact\ duration}\, c_{cost\ per\ minute} \tag{2}$$

Each contact duration $t_{i\ contact\ duration}$ is multiplied by the cost per minute $c_{cost\ per\ minute}$. This results in the cost of each contact. Summing up the cost of all contacts over a single year results in the OPEX per year. Note, we have not considered in this paper the current industry practice of booking a set amount of ground station time in advance. As a simplification we assume the ground station is available when the satellite is within its field of view.

5. Results

5.1 Introduction

To evaluate different ground station networks, and hence, the impact on the time difference between the start of the measurement of a given payload over an area of interest and the acquisition of signal with a ground station, as explained in Fig. 1, and the operating cost, all possible ground station combinations are evaluated. The results can be illustrated in a diagram with the above introduced time interval "payload measurement to acquisition of signal" (PM2AOS) on the x-axis and the OPEX per year on the y-axis. The start of the payload measurement and AOS are direct outcomes of the conducted GMAT simulations. An example of such a plot is shown in Fig. 7. The plot shows the results for the Walker satellite constellation 98:24|3|1 with an orbit altitude of 700 km. This constellation can be considered as the reference constellation for the presented studies. All displayed dots represent a combination of ground stations where at least two ground stations form the network. The bigger the dot the more ground stations are used in the network. The plot shows the mean PM2AOS. With the aid of the square, the circle and the triangle marked in Fig.

7, the plot is explained more in detail. The marked square indicates a ground station network in which the mean PM2AOS is ~77 minutes. This means the average time from the start of a payload measurement onboard of a satellite over one of the six introduced areas of interest until this satellite reaches the next ground station of the network is 77 minutes. The OPEX per year for the marked square example is ~25 M€. The operational cost is calculated using the method introduced in Section 4.4. The price per contact minute is assumed to be 10 €/min. For example, AWS Ground Station provides 10 $/min for wideband reserved [5]. Furthermore, the value of 10 €/min allows the cost results to be scaled very easily. If the actual price per minute of contact is, for example, 8 €/min, then the displayed result can easily be multiplied by 0.8 and in this case the operational cost for the marked square would be 20 M€ for one year. For the square, the used ground stations are also indicated in the plot. In this example five ground stations are used: Alaska Satellite Facility, Astron, Papeete, Trollsat and Weilheim.

Furthermore, a red line with several red numbers is displayed in Fig. 7. The red line forms a pareto front, which means that for each point on the red line there exists exactly one other point for which the PM2AOS is lower or for which the OPEX per year is lower. The indicated circle is on the red line. The red number '3' in this case indicates that three ground stations form in this simulation the ground station network (Astron, O'Higgins and Papeete). This means with three ground stations it is possible to have a mean PM2AOS of ~53 minutes and OPEX per year of 9 M€.

Obviously, PM2AOS and operational cost are directly coupled, since a lower PM2AOS signifies more contacts and contact time with the ground, which in turn increases the operational cost. Therefore, certain trade-offs can be assessed, for example, deriving from the pareto front (red line) it is possible to have a ground station network with PM2AOS of 53 minutes with an OPEX of 9 M€ that uses three ground stations. This point is marked by the circle in the diagram. Or if it is desired to reduce the PM2AOS to 20 minutes then an OPEX of ~22 M€ has to be considered. This point is marked by the triangle in the diagram. Interestingly, the ground station network in this case also uses three ground stations (Alice Springs, McMurdo Ground Station and Svalbard Ground Station).

This kind of plot is used to display and compare different studies presented in the next sections.

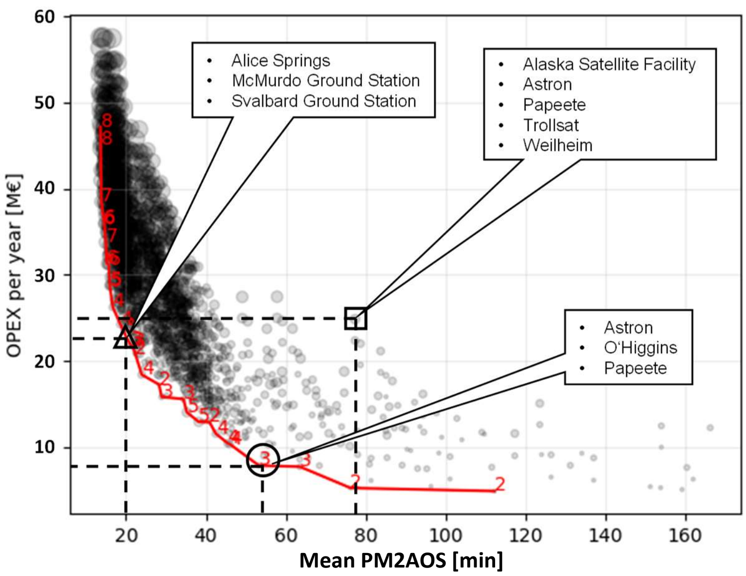

Fig. 7: Mean PM2AOS vs OPEX per year for all different ground station networks

5.2 Ground station networks

Instead of the mean PM2AOS, the 90% percentile is displayed in the following figures. For example, if the 90% percentile of the PM2AOS is 20 minutes, this means that 90% of all calculated PM2AOS is less than 20 minutes. The 90% percentile is used since it is considered to be more meaningful than the average value, in which outliners have a bigger influence on the result.

Of course, the described parameters in Section 4.3 have an influence on the PM2AOS and OPEX per year. Fig. 8 illustrates the influence of the required ground contact time on the PM2AOS. The reference constellation with three planes, 24 satellites and an orbit altitude of 700 km, see Table 1, is evaluated in this case. In the diagram the blue dots show the 90% percentile of the PM2AOS if the duration of the ground contact is not considered. Whereas the black points in the diagram indicate the 90% percentile of the PM2AOS if the ground station contact time is at least eight minutes. As a result, the OPEX is generally lower since less contacts between the satellites and the ground stations are performed. However, looking at the pareto fronts the PM2AOS is slightly increased, since the 90% percentile of the PM2AOS of all dots representing the different networks are higher than the 40 minutes for the black points. For the blue points, there are also ground station combinations below a PM2AOS of 40 minutes. The black points assuming a minimum ground station contact time of eight minutes are used as baseline for the subsequent presented studies.

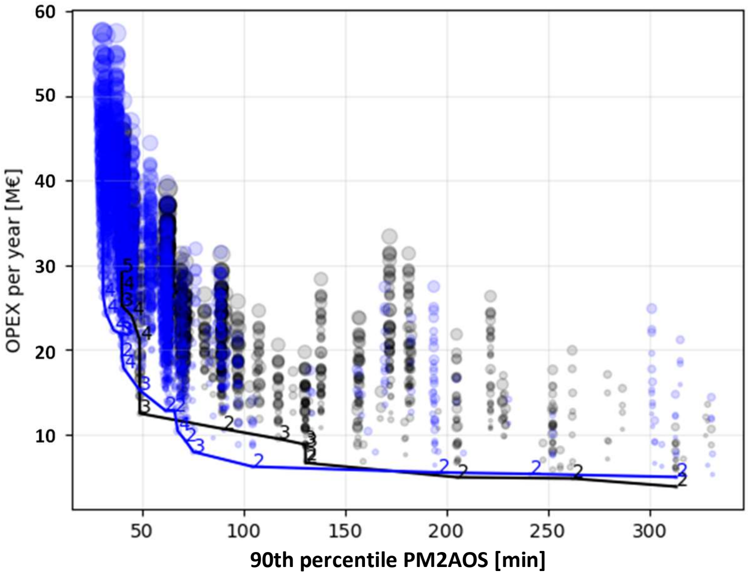

Fig. 8: Comparison of the ground station networks assuming a ground station contact time of at least eight minutes (black) and all ground station contacts irrespective of the contact duration (blue)

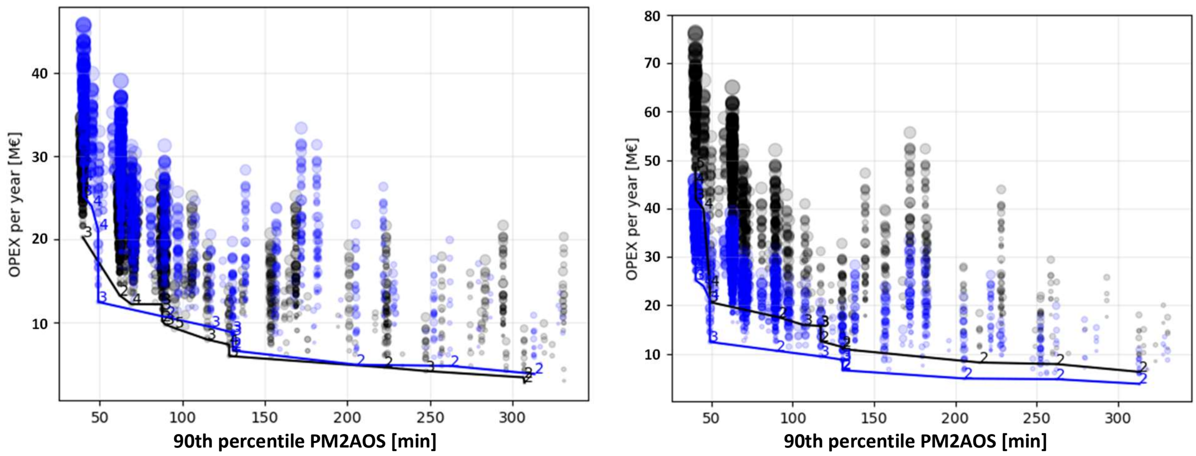

Fig. 9 Left: Comparison of orbital altitude: 600 km (black) and 700 km (blue)
Right: Comparison of number of planes: five planes (black) and three planes (blue)

The left plot of Fig. 9 shows the influence of the altitude on the PM2AOS and OPEX. In the plot the black points represent the Walker constellation with 24 satellites and three plane but with an altitude of 600 km, see Table 1. The blue dots represent the described baseline. At a lower altitude less contacts can be established with the different ground stations, and hence, the OPEX is lower. The PM2AOS is affected as well. If less contacts between a satellite and a ground station are possible, the payload measurement data is transferred later to the ground in many cases. What is noticeable, is the gap between a PM2AOS of ~20 minutes and ~40 minutes for the black points, which does not exist for the higher altitude of 700 km.

The diagram on the right in Fig. 9 shows the result for the Walker constellation with five planes and eight satellites per plane, see Table 1, compared to the baseline. One can observe that more planes, meaning in this case more satellites as well, does not appear to affect the PM2AOS. This is due to the geometry of the setup, since, a particular satellite performing a measurement over an area of interest requires always the same time to reach a certain ground station. Albeit the number of possible measurements and contacts to ground stations increases significantly as well as the OPEX per year. Of course, more planes and satellites decrease the revisit time for the different areas of interest, which is not an aspect investigated further in this paper.

The presented results consider so far only the PM2AOS since this interval is a direct outcome of the simulations as mentioned above. Depending on the type of payload measurement, the raw data received at the ground station has to be transferred to and processed by a data center to obtain the derived information for the customer, see Fig. 1. This delay of transferring and processing the raw data can be added to the displayed data points as a simple offset.

5.3 Onboard data processing

Equipping the satellites with onboard computers that are able to process the raw data of the payload measurements and downlinking the required post-processed data may save time delivering the actionable information to the customer. The left diagram of Fig. 10 compares an onboard processing time of 30 minutes with a processing time of 30 minutes on the ground. The black dots represent the onboard processing results and the blue dots when the processing takes place on ground. The x-axis is changed and represents now the time interval of the start of the payload measurement to the delivery to the customer, see Fig. 1. In the right diagram of Fig. 10 the processing time is increased to 1 hour. The results for the processing on ground are generated by adding the processing time to the results of the already introduced baseline, see black dots in Fig. 8. The diagrams show that onboard processing obtains similar results for a 30 minutes processing time (Fig. 10, left diagram) and the black and blue pareto fronts have a similar shape. For a processing time of 60 minutes, processing the data on ground is evidently faster. The fastest delivery time for on ground processing is ~100 minutes from the start of the payload measurements. The fastest time for onboard processing is ~140 minutes. Since the y-axis is only showing the OPEX per year, there is no change in these values. However, running a data center on ground to process the raw data can increase the overall cost, but having more space certified computational power on board the satellites may result in higher cost. Note, we have not considered a drop in the downlink time and corresponding cost if less data has to be downlinked due to the onboard processing.

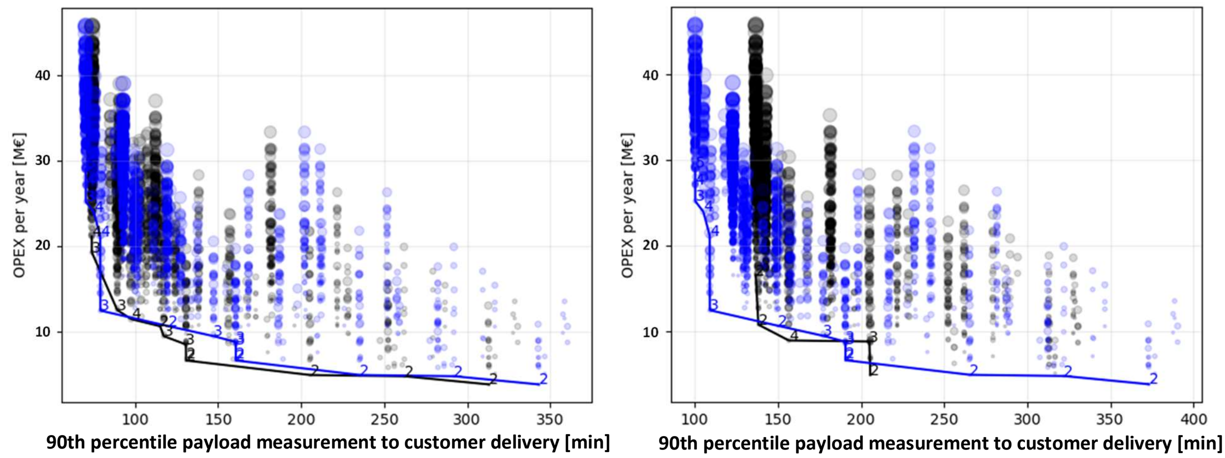

Fig. 10 Left: Comparison of 30 min onboard processing (black) vs 30 min on ground processing (blue)
Right: Comparison of 60 min onboard processing (black) vs 60 min on ground processing (blue)

5.4 Inter-satellite links

In this section the influence of inter-satellite links on the PM2AOS and OPEX per year are discussed. Both types of links, intra-plane and inter-plane, are investigated and their influence on PM2AOS is assessed.

In order to assess and compare the impact of inter-satellite links we use the same ground stations. However, to reduce the computational effort only combinations of at least two and a maximum of three ground stations are considered. Furthermore, the presented results, especially the plotted pareto fronts, show that lower PM2AOS can be reached using only two to three ground stations Therefore, less points are displayed in the following figures.

Fig. 11 shows the comparison between the results of the baseline satellite constellation without inter-satellite links and the results for the same satellite constellation using inter-satellite links. For the inter-satellite links a payload data acquisition and processing time of 5 minutes is assumed. Despite these additional times, the PM2AOS can be reduced significantly to ~20 min compared to 40 to 50 min without inter-satellite links. Furthermore, looking at the obtained pareto fronts, it can be observed that all plotted points for the inter-satellite link assessment are closer together. The pareto front of the inter-satellite links ends at ~50 min of PM2AOS, whereas the pareto front without inter-satellite links ends at a PM2AOS of ~320 min. This means that inter-satellite links enable a network of geographically non-optimal distributed ground stations to reach similar PM2AOS as networks with a more favorable geographic positions of their ground stations.

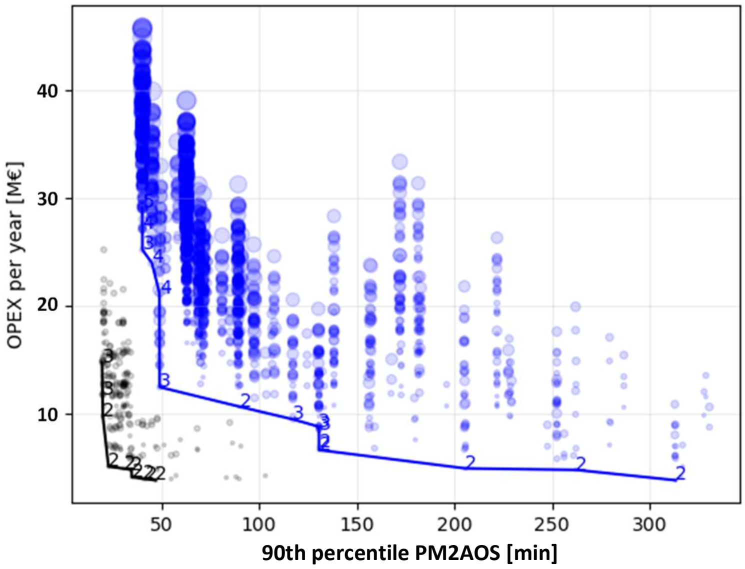

Fig. 11: Comparison of PM2AOS and OPEX per year without inter-satellite links (blue) and using inter-satellite links (black) with 5 minutes payload data acquisition, 5 minutes link connection time and 5 minutes data buffering per established satellite link

Fig. 12 (left) compares the reference constellation consisting of three planes of eight satellite per plane with a constellation of five planes with eight satellites per plane. The PM2AOS cannot be reduced further and the minimal value is ~20 min for both constellations. The OPEX per year for the constellations with five planes is, of course, higher. Since there are more satellites in the constellation more contacts take place with the ground stations, resulting in higher costs. However, all points of the five-plane constellation are close together. Almost all points lie below a PM2AOS of 40 min. The points of the constellation with three planes are more distributed, which means the difference between different ground station networks is further reduced, and hence, the locations of the ground stations can be selected with greater freedom and giving other criteria more weight.

As described above the parameters for inter-satellite links are assumed to be 5 min for data processing, establishing the link and transferring the data. Fig. 12 (right) shows the effect if the parameters are reduced. The blue points and pareto front are the same as already before. For the black points and pareto front the parameters are changed to 0 min for payload data acquisition, taking for example a picture of the area of interest, and 2 min for the required link time and 2 min for the data buffering of the next satellite in the link chain. With these settings, the PM2AOS can be reduced further and the minimal PM2AOS is now ~10 min. There is no effect on the OPEX per year since the number of satellites and contacts to the ground stations is the same.

Fig. 13 shows the comparison of using only intra-plane inter-satellite links (black) with using both intra- and inter-plane inter-satellite links (blue). The use of only intra-plane inter-satellite links is not as effective as utilizing both inter-satellite link types. The displayed black points, representing the different ground station networks, are distributed over a larger area than the blue points for the satellite constellation using both kinds of inter-satellite links. Also, the blue pareto front is displayed for lower PM2AOS. Using more ground stations with more contacts to the satellites, e.g. higher OPEX, both pareto fronts lie closely together at ~20 min of PM2AOS.

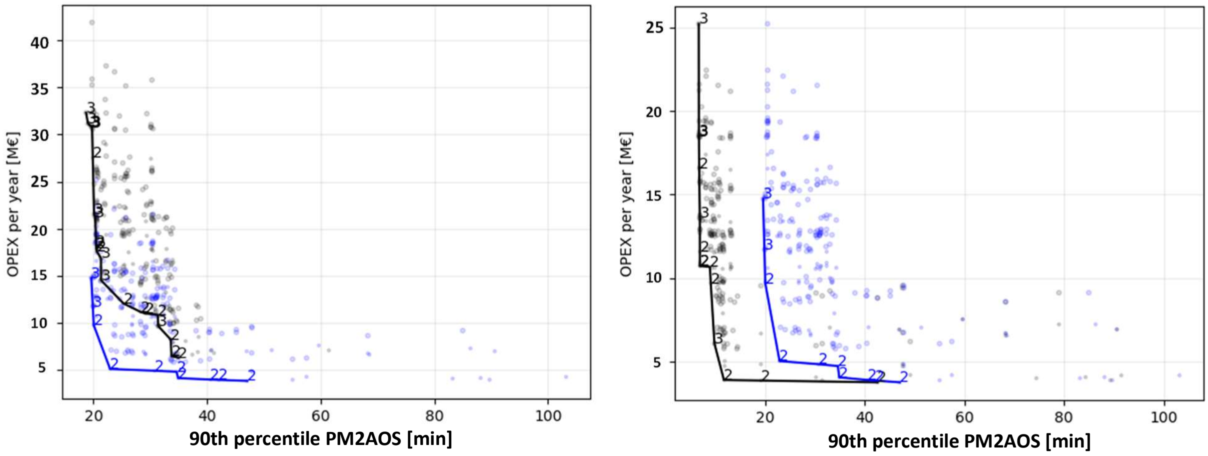

Fig. 12 Left: Comparison of using inter-satellite links for a satellite constellation with three planes (blue) vs a satellite constellation with five planes (black) Right: Reducing the required times for establishing and transferring the data via the inter-satellite links (black) yields a lower PM2AOS

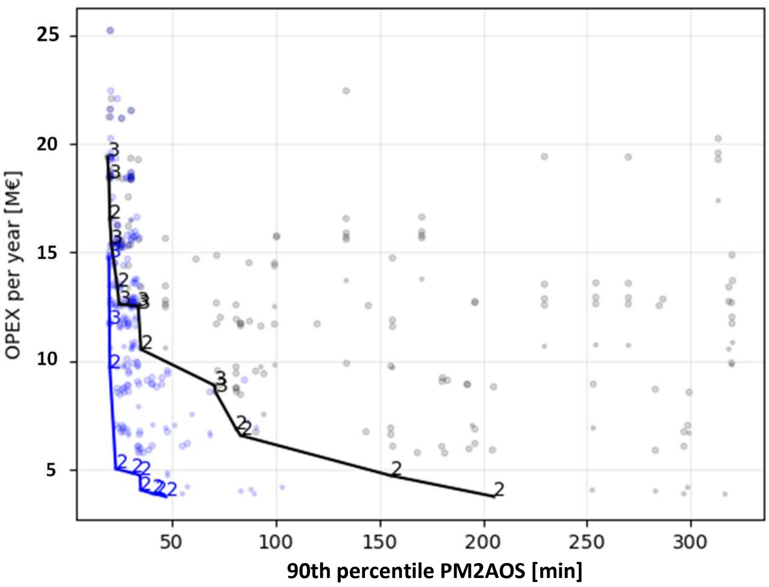

Fig. 13: Comparison between using only intra-plane inter-satellite links (black) and using both inter-plane and intra-plane inter-satellite links (blue)

5.5 Cost

Fig. 14 shows an enlargement of the lower left corner of the comparison of the reference satellite constellation without using inter-satellite links and having inter-satellite link capabilities onboard the satellites of the constellation, see Fig. 11. Various points are marked on the blue pareto front for the constellation without inter-satellite links: a square, a triangle and circle. On the pareto front of the constellation with inter-satellite links one point is marked with a star. The properties of these marked points are summarized in Table 4. The three marked points on the blue pareto front are now compared to the star on the black pareto front.

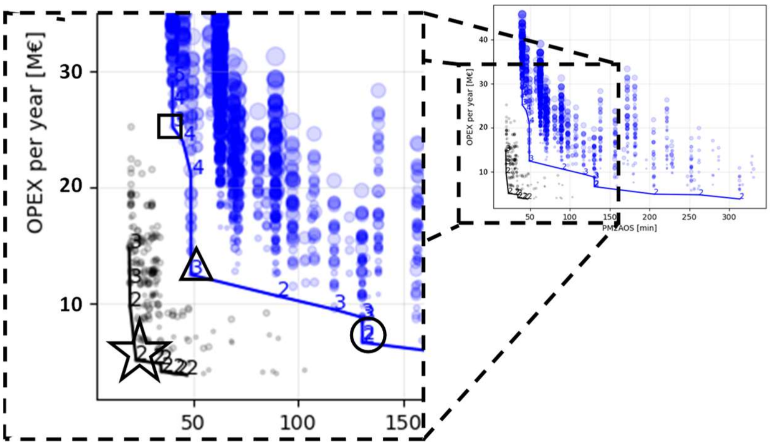

Fig. 14: Enlarging Fig. 11 to show the comparison of the cost assessment

Table 4: Comparing the OPEX of flying and not flying inter-satellite links and the resulting PM2AOS

Point name, see Fig. 10	Inter-satellite links	90th percentile PM2AOS [min] (delta to using inter-satellite links)	OPEX per year [M€] (delta to using inter-satellite links)
star	yes	23 (n.a.)	5 (n.a)
square	no	39 (+70%)	25 (+400%)
triangle	no	49 (+113%)	12.5 (+150%)
circle	no	130 (+465%)	6.7 (+34%)

As shown in Fig. 14 and Table 4, inter-satellite links offer the possibility to reduce PM2AOS and OPEX significantly. However, to equip a satellite or even a constellation of satellites with the technology of inter-satellite links increases the capital expenditure (CAPEX). Therefore, the above presented results can be used to perform a trade-off analysis, as well as a calculating the break-even point for a given CAPEX needed to equip the constellation with inter-satellite links. As stated in Table 4, inter-satellite links offer the lowest PM2AOS accompanied by the lowest OPEX per year. To achieve an equivalent PM2AOS without inter-satellite links and solely a ground station network requires 20M€ more OPEX per annum, i.e. that saving can be used to finance the CAPEX of the inter-satellite links or the number of months required to reach the break-even point. Alternatively, what Table 4 shows is an equivalent OPEX can be achieved for a constellation using solely a ground station network but where the 90th percentile PM2AOS is slower by a factor of nearly 6 compared to employing intersatellite links. Thus, this analysis helps guide the design of the space segment and concept of operations depending on whether the target market is prepared to pay a premium for a reduced data latency or what cost options exist in order to achieve the desired data latency.

Note that the CAPEX has to cover the number of required inter-satellite terminals and their integration, which could be several per each satellite, for example for the different fields of view of a satellite ram, wake, starboard, port and nadir. Since the OPEX are stated per year, depending on the expected lifespan of the constellation or a single satellite, for example a Cubesat, the possible CAPEX for inter-satellite links may be higher if the constellation has to be regularly refreshed. This also depends strongly on the defined replacement strategy if single satellites within the constellation have to be replaced. Note, that our analysis makes no assumption on the satellite platform size.

6. Conclusion and Outlook

6.1 Conclusions

This paper compares different approaches and their impact on data latency from the start of a measurement of a given payload onboard a satellite until the measurement data can be downlinked to a ground station (PM2AOS) or delivered as actionable information to a customer. These approaches are:

- Using a ground station network with up to eleven ground stations and a worldwide distribution
- Using onboard processing to process payload data in order to directly provide the actionable information to the costumer
- Using inter-satellite links with a reduced ground station network

We report that onboard data processing does not reduce the data latency, where in fact, it appears to have a detrimental effect. Whilst onboard processing offers other advantages, such as reducing the amount of data that has to be downlinked, data latency is not one of these.

This paper shows that incorporating inter-satellite links reduces the PM2AOS significantly. PM2AOS is reduced by a factor of at least 2 when using inter-satellite links compared to a constellation relying solely on a ground station network. Inter-satellite links enable a network of geographically non-optimal distributed ground stations to reach similar PM2AOS as networks with a more favorable geographic positions of their ground stations. Importantly, this means the locations of ground stations can be placed where desired when inter-satellite links are employed. The use of only intra-plane inter-satellite links is not as effective as utilizing both inter-satellite link types. This means it is worth overcoming the operational challenges of both higher pointing accuracy and higher relative angular velocities between the satellites to benefit from the reduction in data latency. We also found the interference of the optical link's performance due to sunlight is not considered to have an operational constraint or significant impact on the data latency.

Inter-satellite links offer the lowest PM2AOS accompanied by the lowest OPEX per year. To achieve an equivalent PM2AOS without inter-satellite links and solely a ground station network requires a factor of 5 more OPEX per annum, i.e. that saving can be used to finance the CAPEX of the inter-satellite links or compute the break-even point. Alternatively, a constellation using solely a ground station network achieves a 90th percentile PM2AOS that is slower by a factor of nearly 6 using an equivalent OPEX that constellations with inter-satellite links require.

Thus, the analysis in this paper helps guide the design of the space segment and concept of operations of a LEO satellite constellation depending on whether the target market is prepared to pay a premium for a reduced data latency and shows what cost options exist in order to achieve the desired data latency.

6.2 Future work

In this work, operational potentials of inter-satellite links are presented without defining the inter-satellite technology in detail. Optical inter-satellite links are difficult to execute successfully regarding pointing accuracy and relative velocity of the different satellite to each other, especially when looking at inter-plane inter-satellite links. For this case a minimal angular velocity for rotating the optical inter-satellite link system onboard a satellite needs to be derived.

The contacts of the satellites and the ground stations are not specified in detail. As mentioned before, optical links for space to ground connections are highly dependent on the given weather conditions. For example, a ground station located in an area with less probability of having clouds, would be more preferable to other locations. Therefore, future work could take this into account by defining a probability if a ground station is available for the space to ground connection when a given satellite passing by or not, as well as how to reroute the data transfer through the constellation to an optical ground station that is visible. A first study deals in the assessment of locations for optical ground stations [3].

By using optical links from space to ground, the cost of an optical ground station may also be higher than for a conventional ground station. This will have an impact on the OPEX, which further work needs to account for.

The work also needs to be extended to include and compare the option of transferring the data from LEO to the ground via a GEO satellite.

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