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Nanosatellite Constellation Operational Network Ground Segment Analysis

With the ever-increasing capabilities of the smallest remote sensing satellites, a serious bottleneck is encountered at the space-ground interface. While the satellites are capable of collecting data, downlinking said data is not always straightforward. Analysis of the satellite orbits show that the most beneficial downlink station locations can be found in the polar region. This article introduces the reader to the typical Earth observation orbits, their effects on the data communication periods and describes a possible nanosatellite operational radiocommunication network.

Keywords: **nanosatellite, Sun-synchronous orbit, Earth observation, satellite operations, Systems ToolKit**

We have seen a nanosatellite[2] revolution in the last decade. The milk-carton, shoe box, microwave oven sized spacecraft originally intended to provide the first on-hand experience for university students broke out of that use case and became a viable branch of the space industry. We now see businesses based on nanosatellites in the upstream and also the downstream section of the space value chain.

But while the nanosatellites can provide valuable service, the strict size, weight, power constraints force the designers, operators to invest in the ground segment to overcome the limitations of the satellite. Good examples are the SMOG-P and SMOG-1 satellites, where the satellite is 5*5*5 cm, so it occupies 25 square centimetre when placed onto a surface. At the same time, the surface of the ground station antenna is roughly 160,000 square centimetre (4.5 meter paraboloid reflector[3]), so we could fit more than 6,000 SMOG satellites into the antenna dish.

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[2] Typically the satellites weighing from 1 to 10 kg are called nanosatellites, and 10–100 kg spacecraft are called microsatellites. However, for the purpose of this article, I call all satellites based on the CubeSat standard scaled up to 16 units (approximately 20*20*40 cm) nanosatellites weighing up to about 30 kg. The reason behind this is that these satellites are built from similar components, based on a similar methodology. Above this, different design and manufacturing practices are used.

[3] BME–GND, s. a.

This article analyses another limitation of the nanosatellites, namely, the downlinking of the data collected. Bigger remote sensing satellites regularly use geostationary communication satellites to relay data to the ground stations, but realising this on a satellite literally the size of a shoe box is, while not impossible, certainly impractical. However, a solution is clearly available.

1. Introduction to Sun-synchronous polar orbits

A typical application of nanosatellites is Earth observation remote sensing. With advanced (but readily available off-the-shelf) camera technology, it is possible to provide 4–5 metre Ground Sampling Distance electro optical (visual or infrared) imagery from a 500 km circular orbit with a 6 unit cubesat (approximately 10*20*30 cm structure) with a camera based on optics with 90–95 mm front lens diameter.[4] In a 12 or 16 unit body (20*20*30 cm or 20*20*40 cm) one can fit a front lens almost 200 mm in diameter, or if the front lens is square (cut from a circular lens, just like eyeglasses are cut), the effective diameter is around 250 mm. With such a camera, Ground Sampling Distance around 1.5–2 metres is possible from 500 km.[5] However, this data is only valuable, if it can be readily and effectively downloaded.

Remote sensing satellites typically operate on a Sun-synchronous orbit, which is often (but not always) circular.[6] The orbit lies usually 500–800 km above the Earth. With an appropriately selected inclination, the gravitational perturbations caused by Earth force the plane of the orbit to rotate around the centre of the Earth, somewhat less than 1 degree every day. This way the orientation of the orbit relative to the Sun is constant, that is why these orbits are called Sun-synchronous. Sun-synchronicity is very useful for radar satellites. When such a satellite is placed on an orbit perpendicular to the direction of the Sun (the orbit is riding the terminator), the satellite is in constant daylight, and the solar cells can supply energy for the radar without interruption. For optical remote sensing payloads the Sun-synchronicity means that the light conditions on the ground are constant.

However, a satellite moving on such an orbit has relative movement, when viewed from the surface. This is good for remote sensing – we can see almost the complete surface of the Earth, sooner or later, with the exception of the extreme polar regions. But this also means that the data downlink and control stations can only contact the satellites for a few minutes during an overhead pass. Moreover, the closer the data communications station is to the Equator, the fewer the contact times during a day. This limits the amount of data to that can be downloaded, consequently, the amount of data that can be collected, since the onboard storage is limited. Another operational consequence is that whenever the data is collected by the sensor, it will only be available for analysis after it is downlinked, hours or even half a day later. And this is true for the "housekeeping" data also, that is, the telemetry data used by the

[4] Simera Sense MultiScape100 CIS datasheet Rev 3 2020-06-03.
[5] Simera Sense MultiScape200 CIS datasheet Rev 4 2020-06-03.
[6] ESA: Polar and Sun-Synchronous Orbit, 2020.

spacecraft operators to monitor the status of the spacecraft itself; and the command uplink channel is also open only during the overpasses.

But the farther we are from the Equator, that is, closer to the poles, the number of communication windows increases dramatically. This is hardly surprising – the satellite is on a polar trajectory, so it overflies the polar regions on every orbit. So, the closer to the poles, the better – up to a limit.

It is not enough to downlink the data, it must be provided for the analysts to create the usable, marketable products. High-capacity, reliable telecommunication connection is necessary between the satellite downlink (or combined downlink and control) station and the data processing facility. That is hard to come by in the polar region. The Arctic is a more or less ice-covered ocean, the Antarctic continent is far from populated landmasses and no fibre connection is available. Geostationary satellites cannot see the extreme polar region, so satellite communications is also limited. We need to find a compromise: we have to find a suitable real estate for the downlink facility sites as close to the poles as possible, but still within the coverage of a geostationary satellite.

The scenario forming the basis of this article is centred on Hungary – our stated space ambitions and objective limitations are related to our place on the Earth geography. Therefore, the geostationary satellite used in this scenario is placed at the 4 degrees West position over the Equator, the orbital slot assigned to Hungary by the International Telecommunications Union (currently leased by an Israeli commercial satellite operator). The coverage area of such a satellite is easily mapped onto the Earth surface, so we have to find suitable polar landmasses within this area.

On the Northern hemisphere, the Svalbard Islands are optimal. Because Hungary is a state party to the Spitsbergen Treaty, we can exercise our rights to undertake trade activity on the islands, and a non-military satellite downlink station falls within these rights (military bases for wartime use are prohibited by the Treaty).[7] Building an independent, all-year operational facility on our own would be, however, an unnecessary and extremely hard endeavour, therefore, a suitable host facility should be found. Hungary is an active member of the Visegrád 4 group and Poland operates an all-year research base on Svalbard, specifically, at Hornsund: the Polish Polar Station.[8] This site is selected for hosting the Northern hemisphere polar downlink facility. The Polish Polar Station is located at 77 degrees North, 15 degrees 33 minutes East.

The Southern hemisphere is more problematic. Within the coverage area of the geostationary communications satellite, we find South Africa, but it is not farther from (actually, closer to) the Equator than Hungary, so it would not provide any operational benefits. The Southern end of Tierra del Fuego or the Falkland Islands is only 5–8 degrees farther from the Equator, so the number of overpasses would be comparably the same, just at different times. While even this can be seen as an operational benefit, for real performance increase, one needs to go the Antarctic continent.

Several research bases can be found within the area of coverage at or near the shoreline. Again, Northern (closer to the Equator) sites are better for reachback communication, but worse for the polar-orbiting satellite visibility. A good compromise, and a fitting solution

[7] Treaty of 9 February 1920 relating to Spitsbergen (Svalbard).

[8] The Station's history. Hornsund Polska Stacja Polarna, s. a.

(together with the Northern site) is the Henryk Arctowski Polish Antarctic Station on King George Island, which is also an all-year operational facility. The Henryk Arctowski Station is located at 62 degrees 10 minutes South, 58 degrees 28 minutes West.[9]

2. The reference constellation used for modelling

To analyse the communication windows, a digital twin of an imaginary nanosatellite Earth observation constellation was built with the Analytical Graphics Systems ToolKit software. This software is an industry standard tool used for modelling and analysing complex, multi-domain mission systems, including (but certainly not limited to) satellites.

The orbits of the satellites is based on the KH-11 Crystal constellation, the most advanced defence Earth observation remote sensing satellite system operated by the National Reconnaissance Office of the United States. Two satellites are used, on two polar Sun-synchronous orbital planes, one plane set before local noon, the other plane after.[10]

Both satellites operate on a 450 km altitude circular orbit, Local Time of Descending Node is set at 1000 and 1400, respectively.[11] It is assumed that the satellites carry thrusters for orbit maintenance, so the orbit remains unchanged during the operational lifetime.

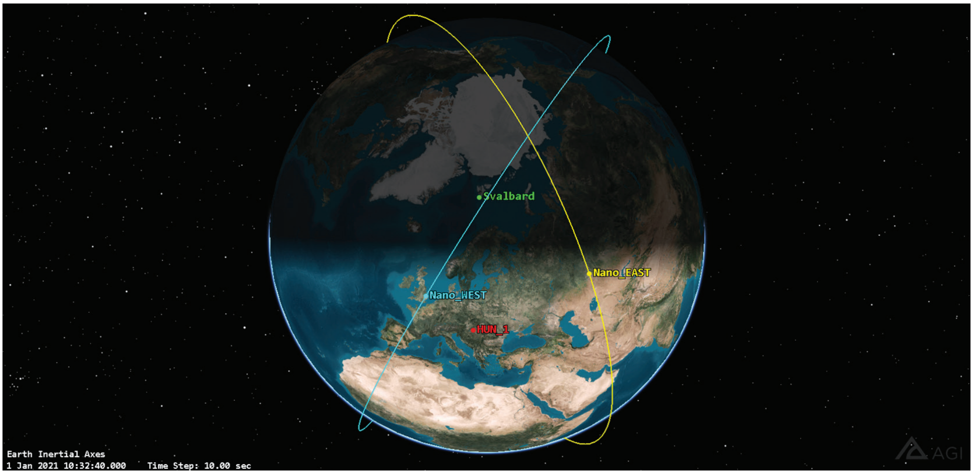

Figure 1

The orbital planes with the two satellites, the Polish Polar Station at Svalbard, and one of the Hungarian stations

Source: Simulated in STK by the author.

9 History of the founding of the Station, s. a.

10 KH-11 Status, s. a.

11 The KH-11 Crystal satellites are launched into elliptical orbits to provide higher resolution imagery of the Northern hemisphere, where most of the targets are located. But this orbit requires frequent and fuel-consuming orbit-maintenance thruster firings, so after a few years, the orbit is circularised by raising the periapsis and lowering the apoapsis. In the scenario used in this article, the orbit is circular from the beginning. The Local Time of the Descending Node values are representative of the KH-11 orbits, but they are rounded to whole hours. This has no practical effect regarding the simulation.

The satellites are equipped with a UHF bidirectional telemetry + control radio and an X-band data downlink radio. The UHF antenna onboard is omnidirectional, the X-band antenna is directional, mounted firmly on the satellite structure; so to communicate with the ground station, the whole satellite body is rotated towards the station by the attitude control system (this makes the remote sensing payload unusable during the communications session).

The 4 ground stations (described in the next section of the article) are also modelled in the Systems ToolKit. The 2 Hungarian stations are placed at arbitrary coordinates (47 degrees North, 19 degrees and 20 degrees East). The polar stations are at their correct coordinates. A 7 degree elevation mask is added to the ground stations to symbolise the possible ground obstacles. Communication is only possible when the satellite is above the mask. The onboard antennas are assumed omnidirectional (even if they are not in reality, this just makes the running of the simulation easier, and during a real operation the attitude control system would keep the antenna pointed for the necessary communication time towards the ground station).

The simulation gives us the time of the rising and setting of the satellite, and the length of the communications window during the transit. The simulation shows the communication opportunities during an arbitrarily selected week, that is, from the 23rd of April 2021 00:00 to the 29th of April 2021 23:59. Only one Hungarian site is included in the simulation of one satellite (HUN_1 site for Nano-EAST satellite and HUN_2 site for Nano-WEST). The second site would theoretically double the communication time, but without a second communication system onboard, the received data would be the same. All times are in Universal Time Coordinated.

3. Simulated communication windows

During the one week long period, for the Nano-EAST satellite, we get the following data from the simulation:

- Access from Arctowski Station: 45 times, 16,330.435 seconds (roughly 4.5 hours, 27.8%) total downlink time
- Access from HUN_1 station: 28 times, 10,324.225 seconds (little less than 3 hours, 17.6%) total downlink time
- Access from Polish Polar Station: 78 times, 32,090.797 seconds (little less than 9 hours, 54.6%) total downlink time
- Altogether, 58,745.457 seconds (roughly 16.5 hours) downlink time

For the Nano-WEST satellite, the number of the communication windows is the same, and the total downlink times are also practically the same, the difference is a few minutes over the whole week.

There are several colliding communication windows at Svalbard, and a few at Arctowski Station (“collision” in this case means that the two satellites arrive to the coverage of the station together, and their respective communication windows overlap at least partially).

This data is extracted from the simulation, via the access analysis function of the Systems ToolKit. By calculating the accesses (that is, communication windows) for the respective stations, it is possible to compile a timetable, listing all the communication opportunities for operations planning. The Systems ToolKit access analysis provides antenna training data (azimuth of the rise above the horizon, azimuth and elevation of the highest point and azimuth of the set).

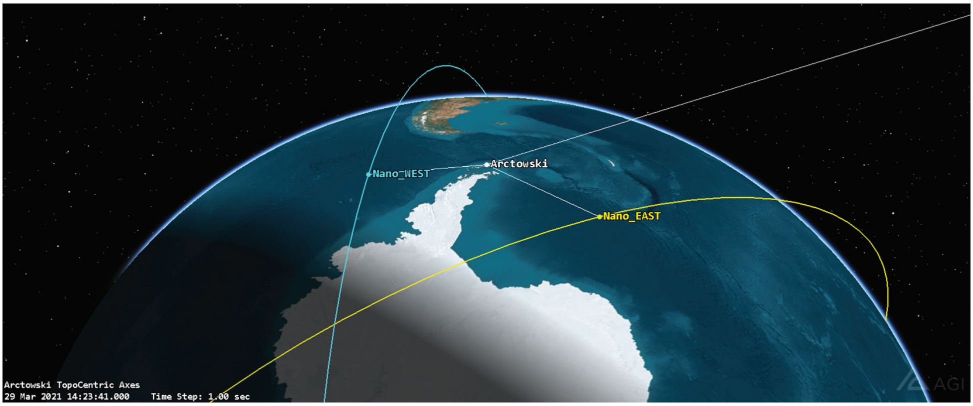

Figure 2

Both satellites are within the communications coverage area of Arctowski Station. The white line going off-screen towards the upper right is the link to the geostationary communications satellite

Source: Simulated in STK by the author.

4. The architecture of the Nanosatellite Operational Network

This section of the article introduces the radio communication systems of a possible multisite nanosatellite downlink and control system. It is designed to provide an optimal number of communication windows with reasonable investments. Even more communication time could be provided with more stations, possibly outside the 4 degree West geostationary position coverage area (that is, visible from another satellite). As of now, I consider this unnecessary. In addition to the investment involved, we need to keep in mind that both the camera and the downlink antenna is installed in a fixed position. So unless the purpose of the satellite is to image the downlink station (an operational scenario hardly justifiable), we have to select whether we download or collect data. The more time we spend for communication, the less remains for imaging.

In the same way, I consider satellite-to-satellite relaying impractical for nanosatellites. Bigger satellites operating in low Earth orbit and spacecraft used for human spaceflight routinely transmit data from the low-orbiting satellite upwards to a geostationary communications satellite to transfer to a suitable ground station. Typical examples are the Tracking and Data Relay Satellite (TDRS) system of the United States,[12] and

[12] Tracking and Data Relay Satellite (TDRS), s. a.

the European Data Relay System and SpaceDataHighway, cooperations of the European Space Agency and Airbus Defence and Space.[13] While intersatellite linking could provide several hours of communication time every day, there are no readily available tracking and narrow beamwidth antennas for nanosatellites today. Widebeam antennas would cause severe adjacent-satellite interference, making frequency coordination and spectrum management difficult. Moreover, without tracking, the whole nanosatellite would need to be trained on the communications satellite, effectively prohibiting the remote sensing payload from operation during the communication time. While the same is true for the ground station communications also, there orbital mechanics limit the communication window. Outside the window the payload can freely operate. In the case of an intersatellite link based operation, we either enjoy the long communication windows (but why, since we cannot collect data), or limit the communication time, just like it is already limited in the ground based case. Laser intersatellite links would be a viable solution (very high datarate, so just a short interruption of the data collection), but fitting a suitable laser terminal into a nanosatellite body (in addition to the payload, power system, thruster and attitude control system, computer and radios) would be very challenging – this only works for bigger satellite bodies as of now.[14]

Therefore, our nanosatellite operational network is based on 4 ground stations: 2 in Hungary for redundancy, one on the Northern and one on the Southern hemisphere polar regions. The polar sites are connected to the satellite operations centre (located in Hungary) via satellite communications links. The Hungarian sites are conveniently colocated with the operations centre(s), or connected via fibre optic and/or microwave links.

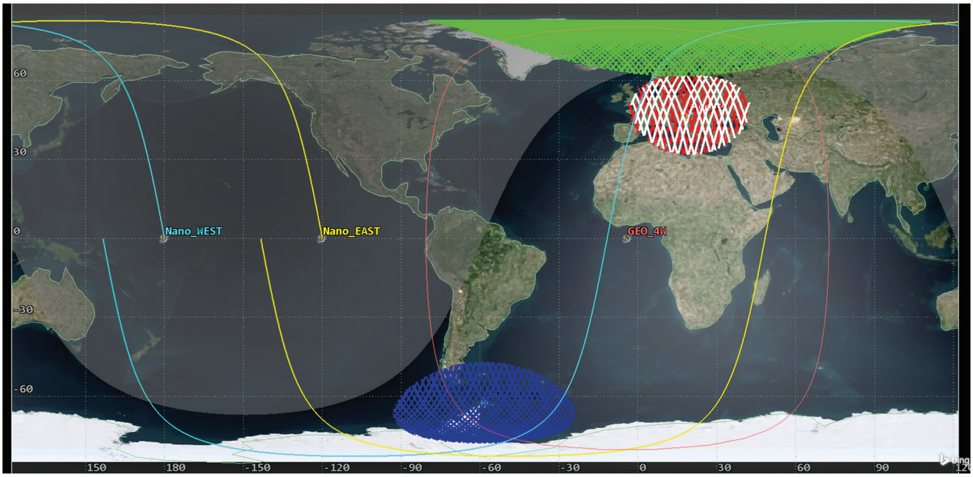

Figure 3

Map of the possible communication windows

Note: When a satellite is the coloured section of the orbit, it is visible to the respective downlink station.

Source: Simulated in STK by the author.

[13] SpaceDataHighway, s. a.

[14] TESAT SMART-LCT datasheet, s. a.

All stations have different advantages and disadvantages. The Hungarian sites can be built the most robust and can have the most reliable connection to the operations centre. They form the backbone of the nanosatellite operations network – although they provide the smallest percentage of the overall communications time. They also have a legal advantage: a remote sensing satellite is a prime asset for defence and security applications, including the space support of military operations. The international treaties governing the utilisation of Svalbard Islands and Antarctica were written without focusing on space activities (obviously). It is not clear if and how infrastructure built there could be used for military purposes, when the supported military activity is happening far from the facilities. Several times the use of imagery downloaded via the Svalbard Satellite Station (a commercial operation of Kongsberg Satellite Services) by military forces resulted in controversial legal publications[15] and political reactions.[16] By declaring that the polar facilities of the nanosatellite operational network are used only for non-warlike purposes, and any directly war-related activity is conducted via the Hungarian sites (if at all), we can avoid such situations.

Serious consideration is necessary to decide whether command uplink should be added to the remote sites or not. The numerous communication time windows provided by these stations increase the operativity and responsiveness of the satellites. But very strong cyber defence safeguards are necessary to prevent the unauthorised access to the satellites via those remote, potentially unmanned sites. Therefore, the safest way is to provide telemetry and data downlink there, this way cybersecurity can be rock-solid.

At the same time, the polar stations provide most of the data throughput and fast access times. Since the nanosatellite is not stationary relative to the observer (the downlink station), the satellite rises above the horizon, transits the sky and then sets. Therefore motorised tracking antennas have to be installed. These tracking antenna mounts must be certified for the environmental conditions expected at the polar locations. The mounts can (and have to be) serviced in-person during the local summer, and they are expected to operate during the local winter remote-controlled. To protect them from the elements (wind load, icing), they must be placed inside a radome. It must be pointed out that the operation of the polar sites is not essential for the safety and usability of the nanosatellites, they just provide extra communication time. Therefore, while losing one or both sites because of a technical problem would severely hurt the performance of the system, it would not cause any danger to the operations.

At the polar stations satellite communications antennas have to be installed. On Svalbard, the elevation angle towards the communications satellite at 4 degrees West is only 3.8 degrees. This is very low, and while it does not prohibit the successful installation of the link, it causes serious challenges. Careful consideration is necessary when selecting the antenna site. The elevation angle at the Henryk Arctowski Station is 7.3 degrees, a much more moderate value. Since the telecommunication satellite is stationary relative to the observer, these antennas do not need to be motorised.

[15] Erik Lieungh, 'Hevder satellittstasjonen på Svalbard blir brukt til krigføring', 09 November 2011.

[16] Erik Lieungh, 'Ingen kontrollerer datastrømmen fra satellittene', 09 November 2011.

The number of antennas at the polar sites depends on the operational tempo. We can safely assume that for telemetry downlink and command uplink one set of antenna is enough, since these operations are comparably fast. To determine the number of sensor data downlink antennas, we have to calculate how much data needs to be downloaded and the time necessary for it.

Based on the MultiScape cameras by Simera, we can assume at most 128 Gigabytes of data to be downloaded, which is 131,072 Megabytes (this is the data of a 2,000 km long strip of imagery for the 200 type camera, or 4,500 km strip for the 100 type). We can also assume, based on various commercially available X-band datalink radios, that the average downlink datarate is around 50 Megabits/second, that is, 6.25 Megabytes/second. The time to download the complete storage is around 21,000 seconds, roughly 6 hours. Careful management of the data collection is necessary, to avoid the generation of imagery which must be discarded after download, because this is roughly two and a half days' worth of communication time!

Because the polar stations cover a significant part of the orbit, "collisions", that is, overlapping satellite arrivals are present, especially at Svalbard. This is not necessarily a problem for the telemetry and control communications, but it would cause significant data loss, unless two downlink antennas are installed. It is absolutely important for Svalbard, and nice to have at the Arctowski Station.

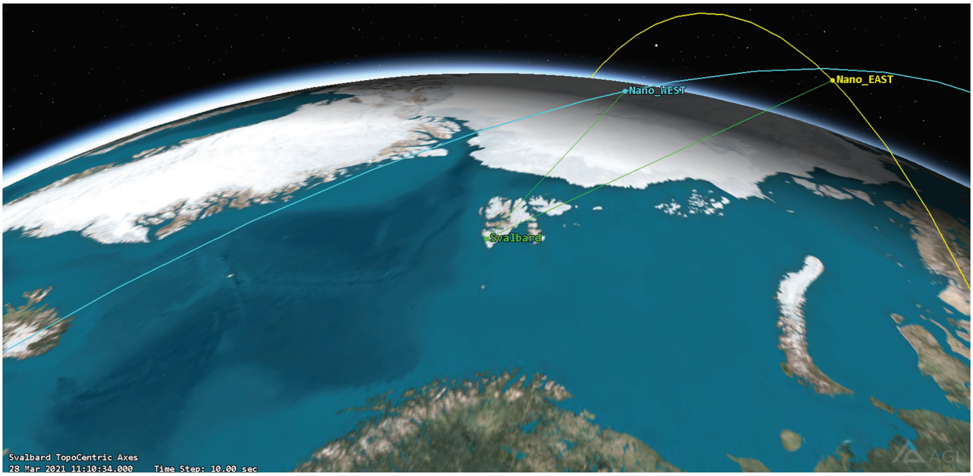

Figure 4

Both satellites are within the communication coverage of Svalbard

Source: Simulated in STK by the author.

Sufficient storage capacity needs to be installed at the remote sites. The reason behind this is that the throughput of the reachback satellite link most likely has significantly lower capacity. So the operational pattern of the remote site is store-and-forward. The exact throughput will have to be determined knowing the actual satellite (frequency, EIRP) and ground station (antenna, amplifier) parameters for the link budget calculation. But again we can see the advantages of the remote sites, that is, the data can be downloaded in shorter segments, within manageable timeframes, and while the satellite completes the next orbit, the data can be brought home via the slower VSAT link.

5. Summary

With the recent advancement of nanosatellite technology, we can now observe a bottleneck at the space-ground interface, specifically, the ability to download the enormous amount of data collected by a satellite. While it is possible to increase the datarate of the downlink up to a certain limit, this does not solve the problem of timeliness – however fast one can download, the download can only start when the satellite is within line-of-sight to the ground station.

Since a typical Earth observation remote sensing satellite travels on a polar orbit, it is logical to locate the ground stations in the polar regions. But the way the data must travel does not end at the ground station, so we also have to take the means to transport it to the place of the procession into account. Practically, this means satellite communications, which limits how close to the poles the ground stations can be placed.

In this article I described, based on a hypothetical two-satellite remote sensing constellation simulated in Systems ToolKit, a nanosatellite operations network consisting of 3 ground station locations (since the two stations in Hungary can be considered one), one at the North pole, one at the South pole, and one active and one alternate station in Hungary. The polar stations are located at Polish research bases, and they are connected to Hungary via VSAT links provided by a satellite at the orbital slot assigned to Hungary, 4 degrees West over the Equator.

The results of the analysis show that such a network architecture is immensely beneficial, as it is able to increase the communication time roughly by a factor of 6.

It is recommended therefore, to plan with polar ground station infrastructure, if and when a nanosatellite constellation is being built to support defence and security operations.

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