A brief survey on the availability of satellite air pollution data

Jernej Cukjati, Domen Mongus, Borut Žalik
University of Maribor, Faculty of Electrical Engineering and Computer Science, Koroška cesta 046, SI-2000 Maribor, Slovenia
jernej.cukjati@um.si

Abstract. Satellite air pollution data sources are presented in this article. Satellite missions are listed and described, and corresponding instruments measuring the concentration of greenhouse gases or other parameters that affect air pollution. Main data hubs are enumerated, and other platforms providing access to the data in different formats. Some platforms contain tools and services that have the capabilities to process and store the satellite data further. Most of them also provide the visualisation of the data, and other simplifications for data selection.

1. Introduction
One of the main problems in modern times is air pollution. The air pollutants may release large amounts of emissions. Most of these emissions are hazardous for human health. Every year millions of people die prematurely because of poor air quality [1, 2]. Governments have addressed this issue and started working towards reducing the contamination. For monitoring the pollutants around the whole globe, space agencies have planned several Earth Observation (EO) missions. They equipped their satellites with sensors to measure greenhouse gases and other aerosols. To raise awareness, governmental agencies made these data freely available to the public through various online platforms.

The main objective of this article is to provide an overview of different air pollution monitoring satellite systems, together with open platforms for data distribution and tools for their processing. Even though most of the data providers made the data freely available to the public, some platforms offer certain services that require paid membership. In addition to the plain data, they most commonly offer computational power and storage for users to process and analyse large amounts of the information easily. Most of these platforms also provide tools for visualisation and data interpretation [2–5].

In the reviewed literature Marč et al. [6] summarised information about satellite devices and other tools used in remote monitoring of air quality. The satellite name, instrument, starting year of the measurements and the role of environmental monitoring were listed in this article. Duncan et al. [7] provided a list of platforms and tools for accessing the satellite images. Bowman [8] presented ground networks and satellite instruments measuring ozone. The paper also described air quality monitoring systems in general. Streets et al. [9] reviewed major satellite instruments detecting emissions. The review of the history of air quality monitoring satellite missions is made including satellite platforms, space agencies, equator-crossing time, instruments, operational periods, measurement parameters, and observed pollutants. Abdelsattar [10] presented the capabilities of different satellite instruments measuring air pollutants according to the spatial and temporal resolutions. In various reviews authors have made a summary of satellites and instruments measuring air pollutants. However, summarisations
in the reviewed literature are either outdated, or do not provide the information where the products for specific instruments might be available.

This paper consists of 5 Sections. In Section 2, satellites and their instruments are presented briefly. An example of a platform providing the fused data is given in Section 3. Section 4 brings discussions, while the article is concluded in Section 5.

2. Satellite data
In comparison to the ground stations, satellite instruments capture relatively large areas. Even though temporal coverage and spatial resolution is low in general, they are still a key part of air quality measurements in regions where other data are not available. In this Section, satellites measuring air pollutants, or parameters from which users can derive pollution data, are presented briefly.

2.1. ERS-2
ERS-2 was an ESA EO mission, with a satellite launched in 1995. The satellite carried a sensor called Global Ozone Monitoring Experiment (GOME). GOME was intended for atmospheric ozone research. It delivered the data on stratospheric and tropospheric profiles of ozone, distribution of atmospheric aerosols, and measured NO2, OCIO and BrO. The instrument provided the global coverage in less than 3 days. The horizontal resolution of the instrument varied, from 40×40 km² up to 40×320 km², while the vertical resolution for ozone was 5 km. After many failures onboard and surpassing its life expectancy, the satellite stopped working in 2010 [11, 12].

2.2. Envisat-1
Envisat-1 was a satellite that was active from the start of 2002 to the end of 2012. On board it carried the Medium Resolution Imaging Spectrometer (MERIS), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) and Global Ozone Monitoring by Occultation of Stars (GOMOS). Instruments had a revisit rate of up to 3 days, except for SCIAMACHY, which had coverage up to 6 days. The MERIS had the spatial coverage of 300 m, with one of its products being Aerosol Optical Thickness (AOT), which was shown to be correlated directly to the density of the PM particles. MIPAS had a vertical resolution of around 3 km, SCIAMACHY a horizontal resolution of 30×60 km², and GOMOS a vertical resolution of 1.7 km. The last three instruments measured the variety of greenhouse gases listed in Table 2 [13–15].

2.3. Satellites from the Sentinel missions
A Copernicus is the European Union (EU) EO programme. Its goal is to monitor the Earth, its environment and ecosystems. As part of this programme, a new family of satellites was launched, known as Sentinels [2, 16].

The first satellites from the Sentinel mission that provided the AOT data were Sentinel-3 satellites. The mission Sentinel-3 consisted of two satellites. The first was launched in 2016, and the second one in 2018. It carries multiple instruments. The instruments that provide the data on aerosols are called Sea and Land Surface Temperature Radiometer (SLSTR) and Ocean and Land Colour Instrument (OLCI) [17]. The pixel size is 9.5×9.5 km² [18]. The OLCI provides the data in less than 2 days, and SLSTR in less than 4 days [19, 20].

The satellite that provides the greenhouse gases’ images is the Sentinel-5 Precursor (Sentinel-5P). The satellite was launched in 2017, with data availability since 2018. It is planned to provide at least 7 years of services. It monitors the atmosphere, and has the revisit time of less than a day [21].
The satellite measures air quality and stratospheric ozone. The instrument provides the data on a multitude of trace gases, including $O_3$, $SO_2$, $NO_2$, $CO$, $CH_2O$, and $CH_4$ [2]. It also measures the cloud and aerosol data [22]. The instrument has a swath width of ~2600 km on the Earth's surface. The typical pixel size (near nadir) is $7 \times 3.5$ km$^2$ for all spectral bands, except for the UV1 band ($7 \times 28$ km$^2$) and SWIR bands ($7 \times 7$ km$^2$) [23].

The Copernicus provides free usage and reusage of the Sentinel satellites’ image data. The European Space Agency (ESA) manages 2 data access points. These are the Scientific Data Hub (SCI Hub), and Copernicus Space Component Data Access (CSCDA) [16]. However, there are more platforms that provide the satellite data, which will be mentioned in the continuation.

Users can download the satellite images through the web interface or python API, called Sentinelsat, which is based on SCI hub access. The data are in Standard Archive Format for Europe (SAFE), except for The TROPOMI data files, which are in NetCDF format [23]. There are many available programming modules that allow the users to interpret and visualise the data, e.g. netCDF4, Panoply and Basemap module in Python [24]. For the Sentinel-5P there is also a Python package called S5P-Tools that contains a set of scripts to download and process air-pollution data. Other tools include VISAN: Cross-platform visualisation and analysis application for atmospheric data, and Basic Envisat Atmospheric Toolbox (BEAT) to analyse the satellites’ data [2, 25].

2.4. MetOp series
The Meteorological Operational (MetOp) series is an ESA programme consisting of three satellites, MetOp A, B and C. The first satellite, Metop-A, was launched in 2006, Metop-B in 2012, and Metop-C in 2018. Each satellite was designed for 5 years’ lifetime and carries 11 different instruments. Two instruments providing the data on greenhouse gases are GOME-2 and Infrared Atmospheric Sounder Interferometer (IASI). IASI delivers the data on ozone profiles, CO, CO$_2$, N$_2$O and CH$_4$. It delivers the data twice a day. It has a horizontal resolution from 1 to 2 m, and a vertical resolution 100 km for CO, CH$_4$ and N$_2$0, and 25 km of horizontal resolution for O3. GOME-2, like its predecessor, provides the data on ozone, NO2, OCIO and BrO. It can also be used for detecting SO2, HCHO and aerosols. Its spatial resolution is 40×40 km$^2$. It provides the global coverage in less than two days [26].

2.5. Terra and Aqua
The Terra and Aqua are a part of a National Aeronautics and Space Administration (NASA) mission. Terra was launched in 1999, and Aqua in 2002. These two satellites are designed to monitor the state of the Earth's environment and changes in its climate system. They cross over the equator at approximately the same local time each day. Aqua has 6 sensors and Terra has 5 sensors. They both have in common the Moderate-resolution Imaging Spectroradiometer (MODIS). MODIS has 36 spectral bands, ranging in wavelength from 0.4 µm to 14.4 µm, and varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). MODIS can provide the data on aerosols, ozone, water vapour, atmospheric temperature, and clouds [27]. The instrument views the entire Earth's surface every 1 to 2 days, producing up-to-date imagery [28]. Additionally, Terra also has instruments called Measurement of Pollution in the Troposphere (MOPITT) and Multi-angle Imaging SpectroRadiometer (MISR). MOPITT measures CO, with a resolution of 22×22 km$^2$. MISR provides data on aerosols with the highest resolution being 0.250 m (all cameras) and 0.275 m (nadir cameras). Both instruments provide complete coverage in around 3 days [29, 30].

2.6. Aura
Aura is the NASA satellite launched in 2004, with a designed 6-year lifetime. It carries 4 sensors: Microwave Limb Sounder (MLS), Ozone Monitoring Instrument (OMI), High Resolution Dynamics Limb Sounder (HIRDLS) and Tropospheric Emission Spectrometer (TES), which are all focused on measuring pollutants in the lower stratosphere and troposphere. MLS provides the stratospheric
measurements on HOCI, BrO, HNO₃, SO₂, CO, CH₂CN and HCN daily, with a vertical resolution from 15 to 5.2 km, and horizontal from 165 to 220 km. OMI provides the data on O₃, NO₂, SO₂, BrO, OCIO, formaldehyde and aerosols. It can distinguish between aerosol types, such as smoke, dust, and sulphates. The products are provided with a resolution of 13×25 km². The complete Earth coverage can be obtained in twelve hours. HIRDLS provides the observations on the concentrations of O₃, H₂O, CH₄, N₂O, NO₂, HNO₃, N₂O₅, CFC 11, CFC 12, ClONO₂. Both HIRDLS and OMI provide data twice a day. TES spatial resolution is 0.53×5.3 km². It provides the global coverage data in less than 2 days. The covered spectral band scan provides the data on CO₂, HNO₃, CFC 11, NO₂, NH₃, CFC 11, CFC 12, O₃, CFC 12, N₂O, CH₄, NO, CO, OCS, HDO, HCl [31–34].

2.7. Suomi NPP
The Suomi National Polar-orbiting Partnership (Suomi NPP) is a satellite launched in 2011. It contains 5 instruments: Advanced Technology Microwave Sounder (ATMS), Visible/Infrared Imager and Radiometer Suite (VIIRS), Cross-Track Infrared Sounder (CrIS), Ozone Mapping and Profiler Suite (OMPS) and Clouds and the Earth's Radiant Energy System (CERES). VIIRS provides the data on aerosols, fires, and smoke. CrIS and ATMS together form the Cross-track Infrared Microwave Sounding Suite (CrMSS), which provides atmospheric vertical moisture, temperature, and pressure profiles [35].

2.8. NOAA-20
The National Oceanic and Atmospheric Administration-20 (NOAA-20) is a satellite active from 2017. NOAA-20 features five similar instruments to Suomi NPP: VIIRS, CrIS, ATMS, OMPS-N, and CERES-FM6. NOAA-20 has a design life of seven years, and it circles the Earth in the same orbit as Suomi NPP. However, the two satellites are separated in time and space by 50 minutes [36].

The data can be viewed through the NOAA data explorer [37]. Additionally, other ways are provided for accessing the data [38]. For example, one way is through the Comprehensive Large Array-data Stewardship System (CLASS). CLASS is an electronic library containing the satellites’ data. The available data are derived from the Polar-orbiting Operational Environmental Satellite (POES), Geostationary Operational Environmental Satellite (GOES), and NOAA-20 [4]. The data are also available through FTP, Global Telecommunications Service (GTS), EUMETCast, and many others [38].

A Community Satellite Processing Package (CSPP) is available for further processing and interpretation of the satellite data. CSPP is a collection of software systems for processing data from meteorological satellites, precompiled for 64-bit Intel Linux. The primary goal of CSPP is to support users who receive satellite data via a direct broadcast, and to create higher level products and images in real time. CSPP supports products from multiple satellites, including Suomi NPP, NOAA-18/19/20, Metop-A/B, Terra and Aqua [38].

2.9. PARASOL
PARASOL (Polarisation and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar) was a science mission of the French National Centre for Space Studies (French: Centre national d'études spatiales, CNES). The mission consisted of one satellite launched in 2004, carrying a POLarisation and Directionality of the Earth's Reflectances (POLDER) instrument. It detected aerosols, and provided daily coverage, and spatial resolution of 6×7 km². The PARASOL mission ended in 2013 [39].

2.10. CALIPSO
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is a collaborative NASA/CNES project. The satellite was launched in 2006. The instrument onboard, Cloud-Aerosol Lidar with Orthogonal Polarisation (CALIOP), provides daily data on the vertical distribution of aerosols. The product has 5 km of horizontal resolution and 60 m of vertical [40, 41].
2.11. GOSAT and GOSAT 2
The Greenhouse Gases Observing SATellite (GOSAT) is a Japan Aerospace Exploration Agency (JAXA) satellite, launched in 2009. It carries two instruments: The Thermal and Near infrared Sensor for carbon Observation Fourier-Transform Spectrometer (TANSO-FTS) and TANSO Cloud and Aerosol Imager (TANSO-CAI). The TANSO-FTS provides the data on aerosols with a resolution of 500 m for bands 1-3, and 1500 m for band 4. TANSO-CAI provides the data on CO₂, CH₄ and O₃, with a resolution of 10,500 m. The global coverage is provided in 3 days. GOSAT 2, was launched in 2018, and carries TANSO-CAI and TANSO-FTS-2. The difference between the versions of TANSO-FTS is in its larger spectral range, allowing TANSO-FTS-2 to detect also CO and NO₂ [42, 43].

2.12. Other data platforms
Besides the data access points mentioned before, several other platforms exist that provide the satellite and other data, or offer services to store and/or process them [2–5]:

- Copernicus data and information access services (CREODIAS)
- LandViewer
- EarthExplorer
- NASA’s Earthdata
- Remote Pixel
- Brazil’s National Institute for Space Research (INPE), online satellite image catalogue
- The registry of Amazon Web Services (AWS)
- Zoom Earth
- NASA Worldview

3. An example of data fusion: The European Centre for Medium-Range Weather Forecasts
To ensure more accuracy we can combine the data from different sources. Most commonly, the ground station and satellite data are combined. Going a step further, the primary data with additional parameters and different simulation models are merged to improve the results.

One of the organisations that provides this kind of data is the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF is an independent intergovernmental organisation supported by 34 States. It is a Research Institute and a service producing numerical real-time forecast weather predictions, and maintains the archives of the meteorological data. ECMWF produces operational ensemble-based analyses and predictions that describe the range of possible scenarios and their likelihood of occurrence. They are working on different streams of work: Global forecasts and climate reanalyses, numerical weather prediction science, environmental services, serving meteorology and supercomputing. It also provides the air quality analysis and atmospheric composition monitoring. It operates two services from the EU’s Copernicus observation programme: The Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S) [44].

ECMWF has its own Web API. It enables the user to request and retrieve the data via HTTP from the ECMWF data archive. The data request is made using the ECMWF Meteorological Archival and Retrieval System (MARS) [45]. MARS has its own scripting language, and the data are received as NetCDF, GRIB or JSON, depending on the API service used. Python modules are also available for making API requests [46].

3.1. CAMS
CAMS is implemented by ECMWF as a part of the Copernicus programme. It provides the data on emissions, global forecasts, air quality forecast and reanalysis, stratospheric ozone, and UV Information. It offers a range of pollutant species: NO₂, SO₂, PM₁₀, PM₂.₅, wildfire, elemental carbon from fossil fuel
and wood burning, $O_3$, $CO$, $NH_3$, $CH_4$, non-methane volatile compound (NMVOC), Peroxyacetyl nitrate (PANs), $NO$, dust, secondary inorganic aerosol (SIA), birch pollens, olive pollens, grass pollens and ragweed pollens. The majority of these pollutants are forecast from the surface up to 5000 m, however, pollens are forecast exclusively only on the surface level. It also provides the data on surface and upper air temperature, surface precipitation, water vapour, surface radiation budget, earth radiation budget, cloud properties, wind speed and direction. The grid resolution is 0.1×0.1°, and the forecast period is 4 days. It combines space and ground-based measurements. At the time of writing, it provides the data from the Sentinel-1, Sentinel-2, Sentinel-4 and Sentinel-5p missions. It also provides the data based on the ensembles from different models: CHIMERE, EMEP, EURAD-IM, LOTOS-EUROS, MATCH, MOCAGE, SILAM, DEHM, GEM-AQ. Because the service covers the area of Europe, reanalyses are based on validated observations, available when Airbase (the European database) is updated [16, 47, 48].

4. Discussion

Satellites were presented with instruments measuring the air pollutants. The Satellites have different revisit rates and instruments, allowing them to measure pollutants with varying accuracy. The general information about the satellites and their instruments’ capabilities are summarised in table 1 and table 2 [2, 8–11, 13–19, 22–40]. Platforms providing the data were enumerated and described for the presented satellites. These platforms are very similar. Most of them provide access to the stored data via visual and programming interfaces. These interfaces allow users an intuitive way of selecting and downloading the data. The main difference is in the provided data format and number of provided satellite products. Furthermore, some introduced platforms include the simulation models, serving accurate results in time gaps when satellite data are not available.

| Satellite    | Launch year | Mission status                  | Space agency        |
|--------------|-------------|--------------------------------|---------------------|
| ERS-2        | 21 April, 1995 | ended in 2010                   | ESA                 |
| Envisat-1    | 1 March, 2002 | ended on 8 April, 2012          | ESA                 |
| Sentinel-3A  | 16 February, 2016 | planned 7 years, active   | ESA                 |
| Sentinel-3B  | 25 April, 2018 | planned 7 years, active       | ESA                 |
| Sentinel-5P  | 13 October, 2017 | planned 7 years, active     | ESA                 |
| MetOp A      | 19 October, 2006 | planned 5 years, active   | ESA                 |
| MetOp B      | 17 September, 2012 | planned 5 years, active | ESA                 |
| MetOp C      | 7 November, 2018 | planned 5 years, active    | ESA                 |
| Terra        | 18 December, 1999 | planned 6 years, active     | NASA                |
| Aqua         | 4 May, 2002   | planned 6 years, active      | NASA                |
| Aura         | 15 July, 2004 | planned 6 years, active      | NASA                |
| Suomi NPP    | 28 October, 2011 | planned 5 years, active | NOAA and NASA      |
| NOAA-20      | 18 November, 2017 | planned 7 years, active | NASA                |
| PARASOL      | 18 December, 2004 | ended on 18 December, 2013 | CNES                |
| CALIPSO      | 28 April, 2006 | planned 3 years, active      | NASA, CNES          |
| GOSAT        | 23 January, 2009 | planned 5 years, active     | JAXA                |
| GOSAT-2      | 29 October, 2018 | planned 5 years, active     | JAXA                |
Table 2. Comparison between instrument capabilities.

| Satellite          | Instrument | Spatial resolution at NADIR | Global coverage (days) | Air pollutants derived from products                                      | Data availability |
|--------------------|------------|-----------------------------|------------------------|--------------------------------------------------------------------------|-------------------|
| ERS-2              | GOME-1     | 40×40 km² to 40×320 km², vertical: 5 km | < 3                    | O₃, NO, NO₂, SO₂, O₄, NO₃, O₄, aerosols                                 | [49]              |
|                    | MERIS      | ocean: 1040×1200 m², land: 260×300 m² | 1 - 3                  | H₂O, O₂, HNO₃, CH₄, N₂O, NO₂, CFC-11, CIONO₂, N₂O₅, CFC-12, COF₂, CCl₄, HCN, CFC-14, HCFC-22 | [3, 50]          |
|                    | MIPAS      | vertical: 3 km              | 1 - 3                  | O₃, O₂, O₃, NO, NO₂, N₂O, CO, CO₂, CH₄, H₂O, HCHO, SO₂, NO₅, BrO, O₃, H₂O, NO₂, NO₃ | [49]              |
|                    |            |                             |                        |                                                                           |                   |
| Envisat-1          | SCIAMACH Y | 30×60 km²                   | 6                      | O₃, O₂, O₃, NO, NO₂, N₂O, CO, CO₂, CH₄, H₂O, HCHO, SO₂, NO₅, BrO, O₃, H₂O, NO₂, NO₃ | [49]              |
|                    | GOMOS      | vertical: 1.7 km             | 1 - 3                  | aerosols                                                                 |                   |
|                    | OLCI       | 300×300 m²                   | < 2                    | aerosols, ozone                                                           | [51][3][52]      |
|                    | SLSTR      | 500×500 m²                   | < 1                    | aerosols, ozone                                                           | [51][3][52]      |
|                    | TROPOMI    | 3.5×7 km²                   | < 1                    | O₃, SO₂, NO₂, CO, CH₃O₂, CH₄, aerosols                                    | [53][3][52]      |
|                    | IASI       | vertical: 1 - 2 m, horizontal: 100 km (CO, CH₄, N₂O) and 25 km for O₃ | 0.5                    | O₃, CO, CO₂, CH₄, N₂O                                                    | [50][54]         |
|                    | GOME-2     | 40×40 km²                   | 1.5                    | O₃, NO₂, SO₂, OCIO, BrO, BrO, ClO, aerosols                               | [54]              |
|                    | MODIS      | 250 m (2 bands), 500 m (5 bands), 1 km (29 bands) | < 2                    | aerosols, ozone                                                           | [50][55][56]     |
|                    | MOPITT     | 22×22 km²                   | < 3                    | CO                                                                       | [50][55]         |
|                    | MISR       | 0.250 and 0.275 m (local mode), 1.1 km (global mode) | < 9                    | aerosols                                                                 | [50][55]         |
|                    | MLS        | vertical: 15 - 5.2 km, horizontal: 220 – 165 km | < 1                    | HOCl, BrO, HNO₃, SO₂, NO, CH₂CN, HCN                                     | [50]              |
|                    |            |                             |                        |                                                                           |                   |
| Aura               | HIRDLS     | 1×10 km²                    | 0.5                    | CO, CH₃CN, HCN, O₃, H₂O, CH₄, N₂O, NO₂, HNO₃, N₂O₅, CFC 11, CFC12, CIONO₂, aerosols | [50]              |
|                    | OMI        | 13×24 km²                   | 0.5                    | O₃, NO₂, SO₂, and aerosols                                               | [50][52]         |
|                    | TES        | 0.5×5.3 km²                 | < 2                    | CO₂, HNO₃, CFC11, NO₂, NH₃, CFC11, CFC12, O₃, CFC12, N₂O, CH₄, NO, CO, OCS, HDO, HCl | [50][57]         |
|                    | VIIRS      | 375 and 750 m               | < 1                    | aerosols, fires, smoke                                                   | [50][56]         |
|                    | OMTS       | 50×50 km²                   | < 1                    | ozone, SO₂, aerosols                                                     | [50][58]         |
|                    | OMTS       | 50×50 km²                   | < 1                    | ozone, SO₂, aerosols                                                     | [50]              |
|                    | VIIRS      | 375 and 750m                | < 1                    | aerosols, fires, smoke                                                   | [50][56]         |
|                    | POLDER     | 6 x 7 km²                   | < 1                    | aerosols                                                                 | [59]              |
|                    | CALIOP     | horizontal: 5 km, vertical: 60m | < 1                    | aerosols                                                                 | [50]              |
|                    | TANSO-CAI  | band 1-3: 500 m and band 4:1500m | < 3                    | aerosols                                                                 | [49]              |
|                    | TANSO-FTS  | 10500 m                     | < 3                    | CO₂, CH₄, O₃                                                             | [49]              |
|                    | TANSO-FTS-2| all except band 5, 10: 460 m, band 5,10: 920 m | < 3                    | CO₂, CH₄, O₃                                                             | [49]              |
5. Conclusions
Satellite data sources for air quality were presented and compared in this article. Satellites and instruments measuring the air pollution are listed and described in Section 2. The satellites from ESA and NASA are included, that are a part of environment monitoring missions. Platforms storing and serving the satellite data are mentioned in the continuation. An example of a platform serving the fused data is presented in Section 3. The described service, ECMWF, uses a satellite, ground station data and simulations to provide the data on space-time locations, where data from the ground measuring data are not available. The presented satellites and platforms are summarised in Section 4.

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