CSCM27 Visual Analytics Group 9 Project Report: Analytics and Visualisation of UCS Satellite Data

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ABSTRACT

The project described was developed to put into practice all teachings of the Visual Analytics module. It concerns the visualisation of the Union of Concerned Scientists (UCS) Satellite Database in order to make it possible for the public to gain better knowledge about satellites orbiting the Earth. Knowledge levels might be different, which is why our project provides a mix of graphs that follow Schneiderman's mantra: overview first, zoom and filter, and provide details only on demand [1]. All data are represented using well-known views to keep the interface as simple as possible to interact with the data. The structure gives an overview of all satellites, purposes, and orbits allowing users to quickly get initial information.

INTRODUCTION

In today's world of data-driven decision-making, visual analytics is becoming increasingly important. Visual analytics is the process of using visuals, such as charts and graphs, to analyse and interpret data. The goal of visual analytics is to make complex data more understandable and accessible to people. Human-Centred Visual Analytics (HCVA) is a new approach to visual analytics that seeks to incorporate the understanding of human behaviour and cognition into the process. By better understanding how people think and interact with data, HCVA can help create more effective visualisations that are better suited to the user's needs.

HCVA also seeks to create visuals that are more interactive. This means that the user should be able to interact with the data, explore different views, and drill down into the details in order to better understand the data. By making the visuals more interactive, users can better understand the data and make more informed decisions.

In our project, we tried to cater to people's needs and reviews. Our design went through the stages of prototyping and further feedback from users to enhance the user experience.

Satellites have been an integral part of modern life since their invention in the 1950s. They are used for a wide range of applications, from communication and navigation, to surveillance, weather forecasting, and scientific research. Satellites are so important that their launch and operation require a great deal of planning, coordination, and expertise. They can range from a few centimetres to several metres in size, and are usually placed in orbits around the Earth for various purposes.

The Union of Concerned Scientists (UCS) Satellite Database is an invaluable resource for scientists, policymakers, and the general public. It provides a comprehensive catalogue of all known satellites in Earth orbit, from active spacecraft to defunct debris. This wealth of information is invaluable for tracking space activities, understanding the potential environmental effects of space technology, and informing policy decisions.

The database is updated daily and contains detailed information about each satellite, including its orbital parameters, launch date and location, owner, purpose, and lifespan. Moreover, the database is divided into categories based on orbital region, mission type, and owner/operator. This organisation allows users to quickly find and compare data across different types of spacecraft.

MOTIVATION AND AIM

UCS Satellite Database provides comprehensive data on satellites in orbit around the Earth. The motivation behind using the UCS Satellite Database is to provide a comprehensive and reliable source of visualisation on the current activity of satellites in orbit to feed into the growing interest in space.

This database is used extensively by government agencies, research institutions, and private businesses to understand the current state of the space environment and how it is changing over time. One of the aims of this project is to allow the general public to explore satellite information in a simple and interactive way. We have also created some technical visualisations for the more expert audience. To the best of our knowledge, there is a lack of current interactive, public-accessible visualisation for this data. Our visualisation can be a great resource for students and amateur astronomers.

THE DATASET

The dataset used in this project is taken from UCS, The information in the Database was gathered from openly accessible corporate, academic, government, military, scientific, and non-governmental websites. It is free to access. The data was first published in 2005 and updated in 2022.

The data has a limitation where it lists only UN-registered satellites; meaning it does not include all satellites throughout the listed years. The original dataset contains 28 attributes for each satellite and 5466 entries. The data was cleaned by removing entries with blank fields and updating missing formulae, leaving 5377 entries.

To make the data more manageable we chose 12 of the attributes in order to give a mix of three data types - categorical, ordered and continuous. Table 1 describes the attributes used:

Attribute	Description	Data Type
Name	Current Official Name of Satellite	Categorical
Country	Country/Org of UN Registry	Categorical
Users	List of users for example Civil/Military/Government	Categorical
Purpose	List of uses for example - Earth Observation/Communication	Categorical
Class_of_Orbit	Elliptical/GEO/LEO/MEO	Categorical
Longitude of GEO (degrees)	Defines the point above the earth where a geostationary satellite is located	Continuous
Perigee (km)	Point of orbit closest to the earth	Continuous
Apogee(km)	Point of orbit farthest from the earth	Continuous
Eccentricity	Orbit circularity, 0 is a circular orbit, 0 to 1 is elliptical	Continuous
Period	The time it takes to complete one orbit, in minutes	Continuous
Date of Launch	Date the satellite was launched	Ordered
Launch Site	Location of the satellite launch	Categorical

Table 1. Table of Selected Attributes

Orbit Classes

Geostationary Orbit (GEO): A satellite with an altitude of 35,786 km, which is designed to match the rotation of the Earth, so it stays in one place above the equator.

Low Earth Orbit (LEO): A geocentric (circular) orbit with an altitude of less than 2,000 km.

Medium Earth Orbit (MEO): An orbit anywhere between LEO & GEO, but usually approximately 20,000 km.

LITERATURE REVIEW

Satellites have become an invaluable tool in the modern world, providing a range of services that have transformed the way people live and work. A satellite is an artificial object placed in orbit around the Earth, typically for communication and navigation purposes. Satellites are used for a variety of applications, including telecommunications, broadcasting, navigation, weather monitoring, and remote sensing [2].

The history of satellites dates back to the mid-20th century, when the first artificial satellite, Sputnik 1, was launched into orbit by the Soviet Union in 1957. Since then, satellites have become a critical component of global communication and navigation systems, and their use and capabilities have grown exponentially [3].

Satellites are typically classified based on their orbit type and eccentricity. Circular orbits are typically divided into three classes, Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO). LEO satellites orbit at altitudes of up to 2,000 km and provide services such as satellite navigation, satellite Internet access, and Earth observation. MEO satellites orbit at altitudes of up to 35,786 km, providing services such as satellite television, satellite telephones, and satellite radio. GEO satellites orbit at altitudes of up to 36,000 km and provide services such as broadcasting, communication, and navigation [4]. Elliptical orbits are defined by their high eccentricity and the resulting difference in their perigee and apogee locations. These orbits are used by paired satellites in applications such as communications, earth observation and space observation. Their main advantage is having longer exposure periods at the apogee and hence spending little time in the Earth's radiation belt which compromises signal quality [5].

The use of satellites has revolutionised the way people communicate and access information. Satellite communication systems allow for the transmission of voice, data, and video signals from one point on the globe to another, providing global coverage and access to remote and underserved areas. Satellite navigation systems, such as the Global Positioning System (GPS), provide precise location and timing information for navigation and tracking purposes. Satellites are also used for Earth observation, providing a global view of the planet and allowing for the monitoring of natural disasters and environmental changes [2].

The advancement of satellite technology has enabled the development of more sophisticated and powerful satellites. Newer satellites are equipped with more powerful antennas and transceivers, allowing for higher throughput, higher data rates, and improved services. In addition, satellites have become more cost-effective, with smaller, lighter, and more efficient designs that are easier to launch into orbit [3].

The use of satellites is expected to continue to grow in the coming years, as new technologies and applications are developed. With the emergence of new low-cost satellite technology, there is potential for a new era of satellite-based services and applications. As the number of satellites in orbit continues to grow and the capabilities of existing satellites are expanded, the sky is the limit for the future of satellites [3].

However, this is also causing concern about what these satellites are being used for. Although many satellites are used for observation, it is believed that larger countries such as the United States are becoming increasingly interested in military uses, with the possibility that satellites may become weaponised [6]. There is also a growing concern about what will happen to them when they cease to function [7].

The dataset under consideration is of high dimensionality and consists of a very large volume of features. Hence, a visualisation technique must be employed capable of dealing with datasets exhibiting such characteristics. Two of the most widely used visualisation techniques for large high-dimensional datasets are the scatterplot matrix (SPLOM) and the parallel coordinates plot [8]. Whilst SPLOMs are easier to use [9], the parallel coordinates plot is more well-suited for dealing with fuzzy datasets, such as the one in question [10]. Parallel coordinates utilise the spatial positioning of jagged lines across parallel axes to convey individual object information. Whilst, they have a significant limitation in overplotting, they are optimally used in medium volume of features, which allows their data correlation capabilities to be demonstrated [9, 4].

IMPLEMENTED SOLUTION

The implemented solution visualises Satellites' Orbits, Purpose, countries' ownership, and the relationship between orbits, and purpose. One of the views is a parallel coordinate plot. There are interlinked filters between the visualisations and further filtering capabilities are provided to allow for more details. Visualisations can be filtered based on Orbits, Purpose, and Country. Future implementation could include an additional filter for time-scale.

The implemented solution is shown in Figure 1

Figure 1. UCS Dashboard

We designed the dashboard using the following techniques:

Colour

Colour is a powerful tool that can help to communicate complex information quickly and effectively. Colour can be used to enhance visualisations, draw attention to important aspects of data, and add clarity to complex relationships. As it has been shown to be one of the most effective ways to communicate information [9].

In our visualisation, we used hue to represent categorical data, to differentiate between different data points and categories, to show relationships between data points and categories, to draw attention to important elements, and to create a sense of harmony in a visual analytics report. The clustering and density of colours in parts of the graphs, discussed in the results, was a great indication of the increase or decrease of the specific category.

We also used colour saturation on the map to represent the number of satellites used by each country. We used inverted colours where countries with the fewest satellites are darker, so they can be seen more easily. After presenting the visualisations to users they suggested using a logarithmic scale on the data to further enhance the colouring schema which we employed.

Filtration and Interaction

Our visualisation dashboard contains four visualisations, all of which are coordinated with each other and linked by internal selections and filtrations (see the limitation of implementation section). Additional filters were added as a dropdown menu and radio buttons

The Implemented Graphs

Map

The map gives a general overview of the count of satellites according to each country. The dashboard can be filtered by country using a single selection in the map.

Bar Chart

We chose a Stacked Bar chart to show the count of satellites in each orbit throughout the years. The graph can further filter the rest of the dashboard based on a single selection of any of the bars leading to more insight into the different categories of the data. Since this is a common task, bar charts are a fairly ubiquitous chart type to use.

Dot plot

When it comes to satellite purposes changing over time, a 2D visualisation dot plot is the most useful. The graph aimed to present the data as honestly and accurately as it could while avoiding poor designs [12] that might lead to conclusions that do not exist in the data.

This visualisation makes it simple to draw conclusions by allowing the user to directly visualise the functions of satellites and how they have changed over time based on the colour density that is displayed when plotting each purpose.

Parallel coordinates

The parallel coordinates plot is used for the visualisation of the numerical attributes of individual satellites since it uses spatial position to visualise multiple quantitative attributes simultaneously [9]. Such attributes include the perigee, apogee, eccentricity and the period of the satellite. This plot offers efficient visualisation of these attributes which can be categorised by the user in terms of country and purpose. This technique also allows the user to show cluster patterns, which is very useful for demonstration in less knowledgeable audiences. The structured view of these clusters originates from the colouring based on orbit class.

A more knowledgeable user can take advantage of the final “on demand” details taking advantage of the individually-normalised axes to convey relative information about the satellite’s orbit characteristics and through the use of mouseover-tooltip the user can view exact information of the satellite attributes.

Implementation Limitations

1. Due to the huge volume of data, for the second version, we aim to group the data by years through different stages of space exploration.
2. Lazy loading of data is not supported in Altair. Large datasets are one of the weak points of the current Vega-Lite implementation. There are several techniques to overcome this in Altair, we aim to find a workaround to enhance the loading and interactivity of the charts in the next version. Using JSON in drawing the map has limited capabilities when implemented in Altair, which is why when the map was finally presented, it only included countries with satellites and the rest of the countries were not graphed to limit the bugs and workarounds.
3. Filtering countries by clicking on the map did not work fully, we chose to disable the feature for now, and further enhance it in the coming versions. A workaround was implemented by utilising dropdown menus to include all countries.
4. Interlinked graphs are slow when using selection between them. We implement selection filtration between 3 graphs, purpose, orbits and parallel coordinates, to allow for zooming for details and further probing of the data, but the speed of filtration needs to be enhanced.

ALTERNATIVE DESIGNS

To develop the final dashboard, we went through an iterative prototyping process. The first prototype in Figure 2 leveraged the use of maps in a Multiview to represent all the data the Multiview implementations would have included different filtration options to allow for further details of the data.

In our dashboard, we chose to use one map to provide an overview of the data and filter the rest of the dashboard based on the attributes required by the user. For example, the first diagram shows the different satellite orbits, and the second displays the satellites revolving in different orbits. This in turn yields a privilege to the user to select multiple checkboxes and get the desired representation of their result according to their needs. This is then displayed as shown in the third diagram of Figure 2, by selecting multiple checkboxes in which satellites are differentiated on the basis of shape, colour and size, as well as the orbits by colour.

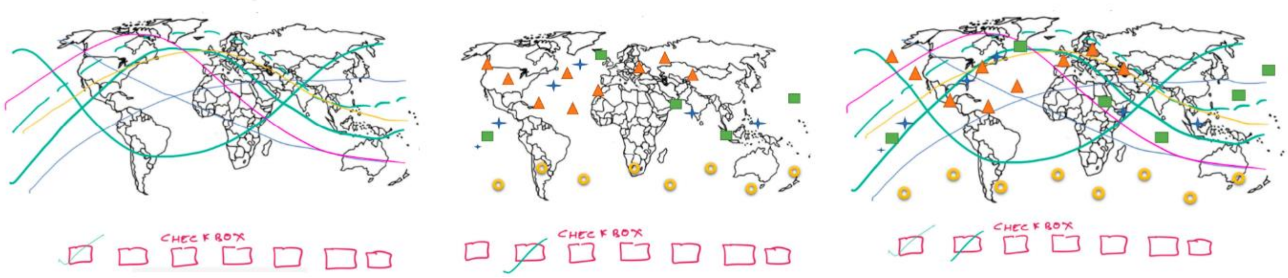

Figure 2. First Prototype

The second prototype in Figure 3 represented data as a set of coordinated multiple views. In all views, colour was used to encode continents and in the primary view, marker size was used to encode the number of satellites. There is a large difference between values for the number of satellites for North America and other continents. This led to tiny marker sizes in some cases, which made it difficult to interact with them. To resolve this issue we set the minimum marker size to 50 square pixels. In order to prevent overlaps between markers we also set the maximum marker size to 700 square pixels.

The coordinated view system was designed to allow users to select a continent and view satellite purpose by year and by orbit type. In the example below, it can be observed that first satellite from African continent was launched in the year 2001, most of the satellites from the African continent are in the lower-earth orbit and the majority of them were launched with the purpose of Earth Observation.

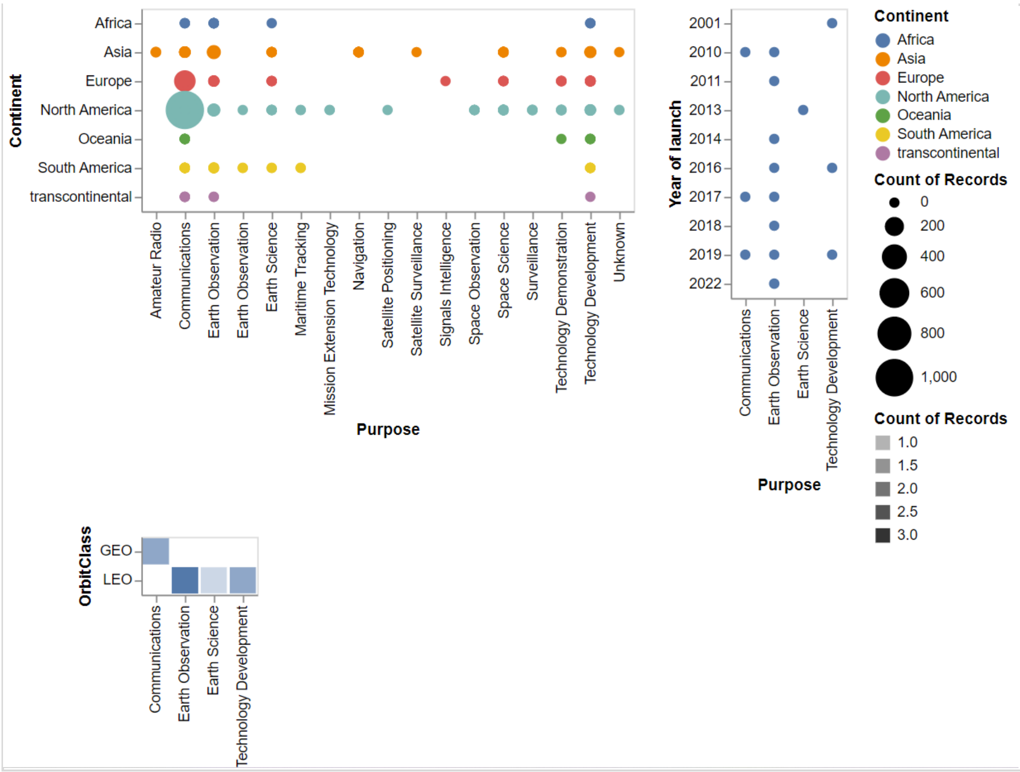

Figure 3. Second Prototype

The final prototype idea in Figure 4 leveraged a multi view approach to show orbits and purposes of satellites according to orbits and country. This was divided into two graphs in our dashboard, purpose and orbits, and further details made possible by selection and filtrations.

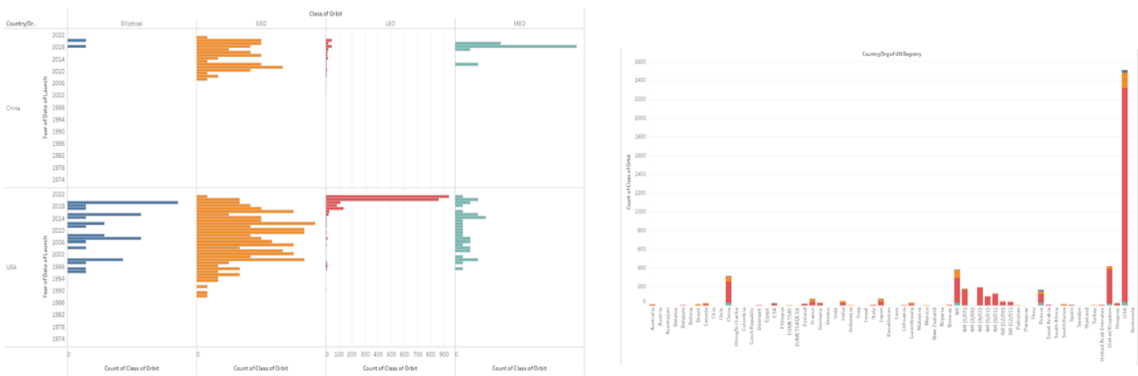

Figure 4. Third Prototype

RESULTS AND HIGHLIGHTS

Satellite Ownership

From the map in Figure 5, we can see that the United States is the country with the highest number of satellites followed by China and then Russia, the countries with the darkest colour have the lowest number of satellite ownership, and countries coloured in black have zero satellites in orbit. The number of satellites owned by each country is shown in the tooltip when hovering over the specific country. A suggestion was made to use a logarithmic data scale, which would help greatly in creating the colour distinction, thereby enabling a better understanding of the satellite's ownership distribution.

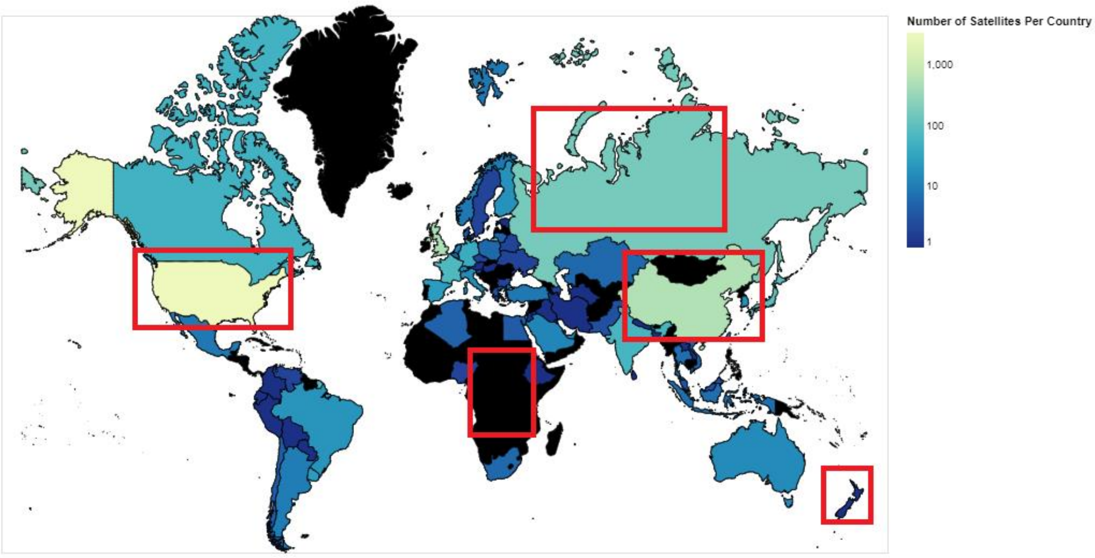

Figure 5. Satellite Ownership Distribution

Purpose of Satellite Usage

The second visualisation shown in Figure 6 provides an overview of the purpose of the satellites over the years. We can see by the clustering of colour that communication over the years has been listed as the main purpose of sending satellites, followed by Earth observation, Navigation, Technology development and finally Surveillance. Communication satellites have been steadily increasing over the years, from 1995 until 2022, a huge number of satellites for communication purposes were launched, interestingly the first satellites documented in this dataset were launched in 1975 for the same purpose. Space science and Navigation satellites were focused on between 2013-2022. Technology development satellites increased between 2011-2022. One satellite for educational purposes was launched in 2018.

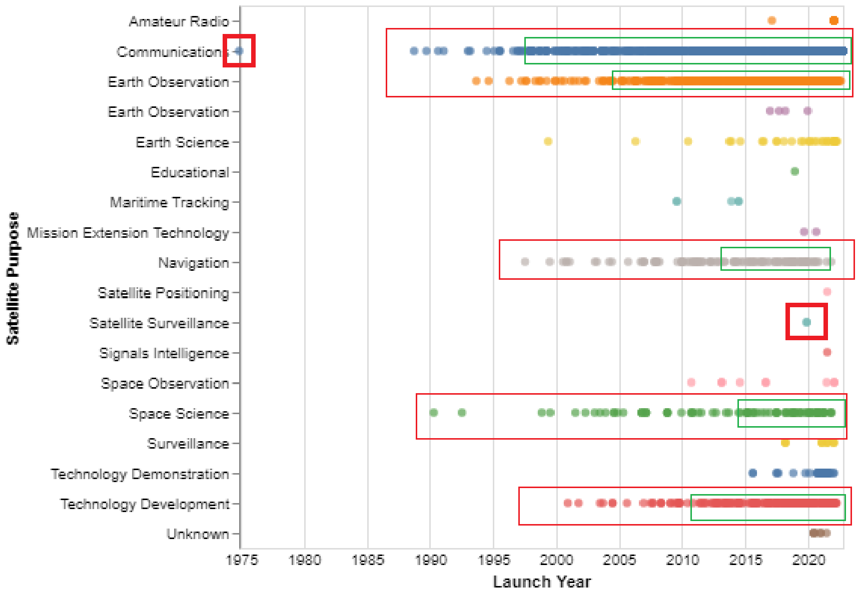

Figure 6. Purpose of Satellites

The purpose of satellites can also be further explored by applying filters according to the orbits of satellites in general or by a single selection of the orbit graph based on the year. The purpose of satellites orbiting in LEO orbit as shown in Figure 7. We can see that the purpose of satellites in this orbit is mainly focused on Earth observation, followed by space science and technology development, while we can see that the majority of satellites in GEO orbit as shown in Figure 7 are communication satellites. Further filters can be applied to give results by the rest of the orbits, the year of launch and the country as needed by the users.

Figure 7. Purpose of Satellites filtered by LEO orbit

Figure 8. Purpose of Satellites filtered by GEO orbit

Satellite Orbits

As shown in Figure 9 we can see that most of the satellites are launched into GEO and LEO orbits, with the majority being in the LEO orbit. The remaining two orbits have very few satellites. We can also see that satellite launchings started to increase in the Year 2014. The year 2021 witnessed the highest volume of satellite launches. When filtering orbits according to purpose, Figure 10 shows communication satellites over the years in the four orbits. The most launched communication satellites were in 2022 but the launches increased between 2019-2022, the lower number in 2022 is not 100% accurate as the data for 2022 is not completely updated yet. Different purposes of satellites according to orbit can be further explored by filtering according to country.

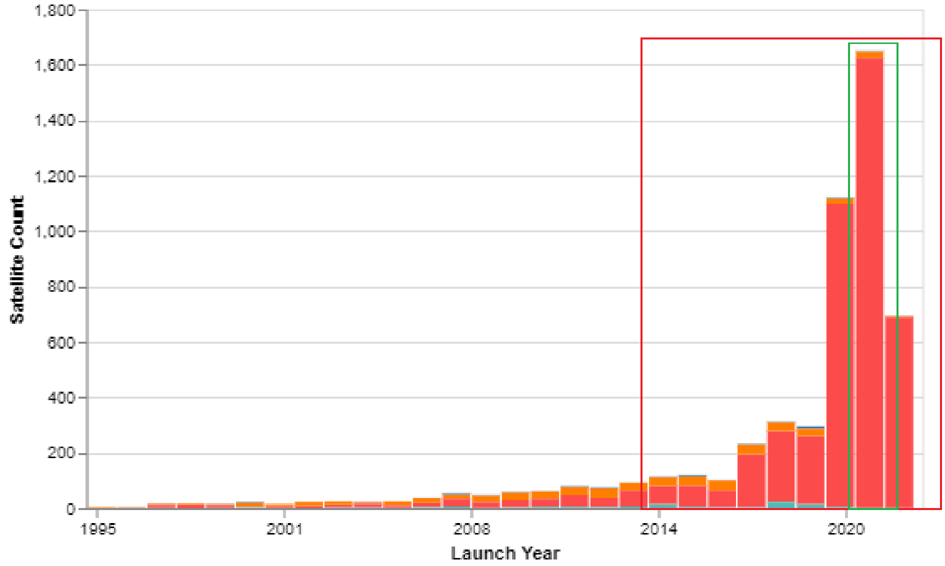

Figure 9. Satellite Orbits

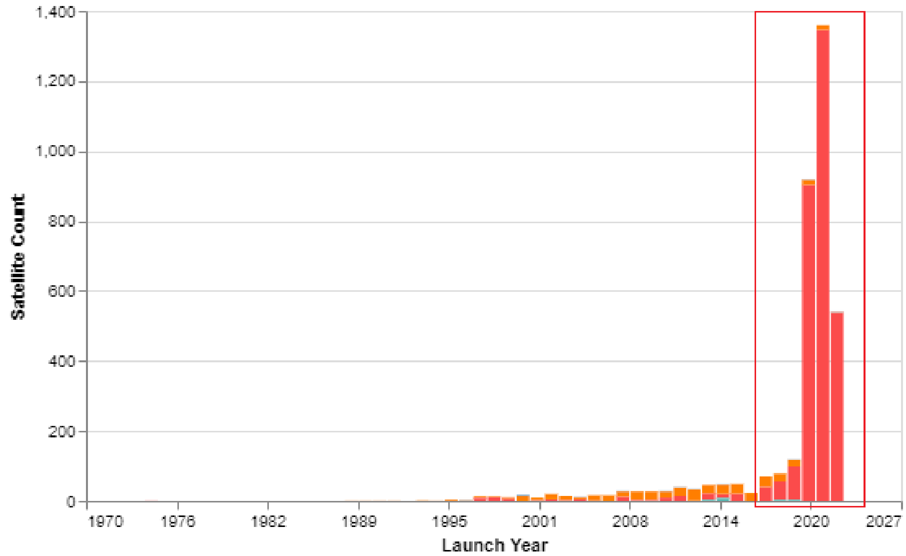

Figure 10. Orbits filtered by Communication purpose

Further data zooming can be realised by clicking on any of the graphs and filter the rest of the graphs according to the selection to show the specific satellites in the orbit according to the year, purpose, and their technical details.

Parallel Coordinates

Considering the general overview of the parallel coordinates plot without any filtering shows four major cluster groups, as shown in Figure 11. These groups can be identified to be Elliptical orbit satellites, and satellites in the LEO, MEO and GEO orbit classes. For the LEO, MEO and GEO clusters it is immediately visible that their eccentricity value is quite small, indicating that satellites positioned in these orbit classes have a circular orbit. Furthermore, the orbit attributes of these clusters are seen, and it is evident that the LEO orbit operates within the smallest perigee, apogee and hence, period values. As expected, satellites within the MEO orbit class cluster are seen to exhibit higher attribute values than LEO but lower than GEO. The final cluster can be identified as Elliptical orbits due to their high eccentricity. This cluster can be seen to incorporate relatively low Perigee and large Apogee, but with lower Periods than the GEO orbit class.

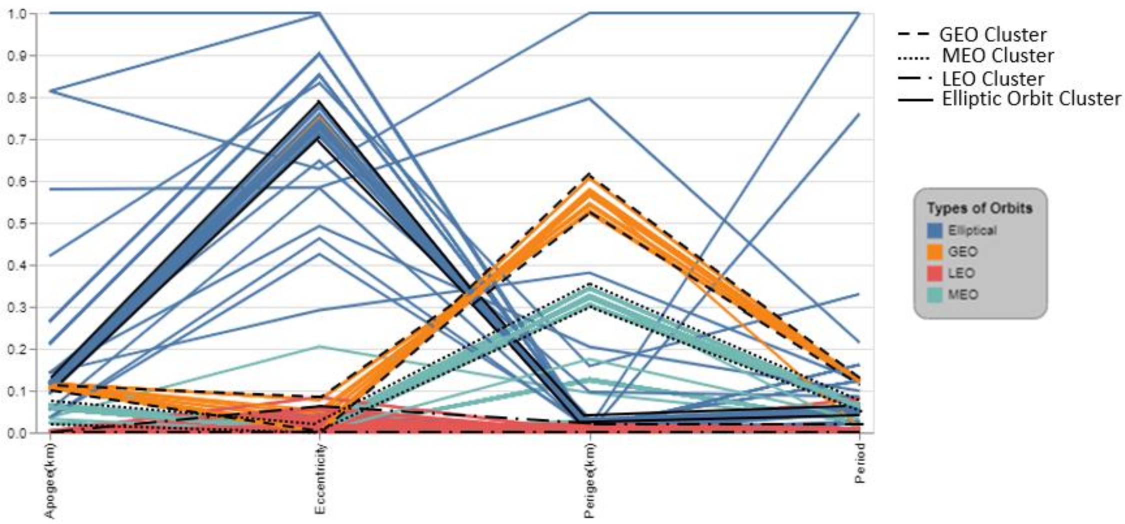

Figure 11. Overview of orbit classes with highlighted clusters

Two exemplary filtering and selection scenarios are to be described to demonstrate the overall visualisation methodology for a practical use of the parallel coordinates plot. Assuming a selection procedure for identifying Russian communication satellite characteristics. In the parallel coordinates plot, shown in Figure 12, it can be seen that the cluster patterns formed in the overview are still somewhat visible with the exception of MEO, indicating communication satellites are not employed within the MEO orbit class. Further comparison with the USA, confirms this assumption, as the MEO orbit class is again not visible.

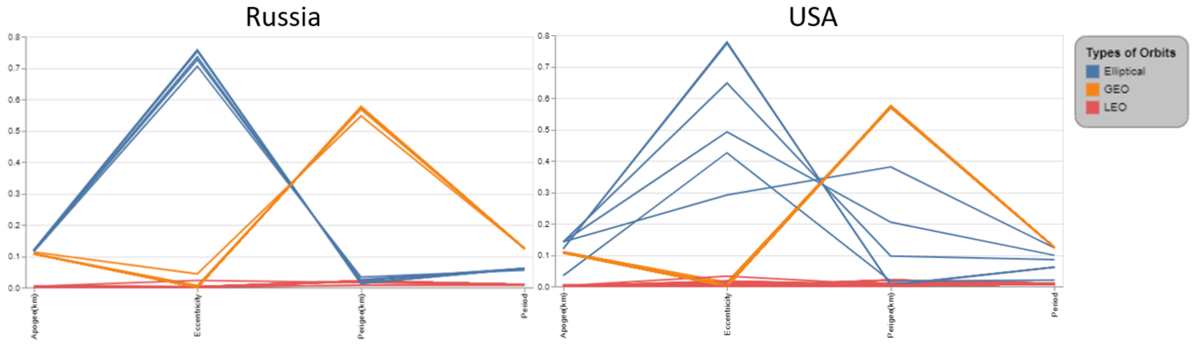

Figure 12. Communication satellites used by Russia (left), USA (right)

A second scenario can be assumed where Earth Observation (EO) satellites employed by China are visualised. It is evident that most satellites are employed in the LEO orbit class, as seen in Figure 13. Comparing these findings with the USA employed EO satellites, indicates that most EO satellites are employed in the LEO orbit class. In addition, it is seen that the USA also uses highly elliptical, high altitude orbits (HEO), and the GEO orbit class for these purposes.

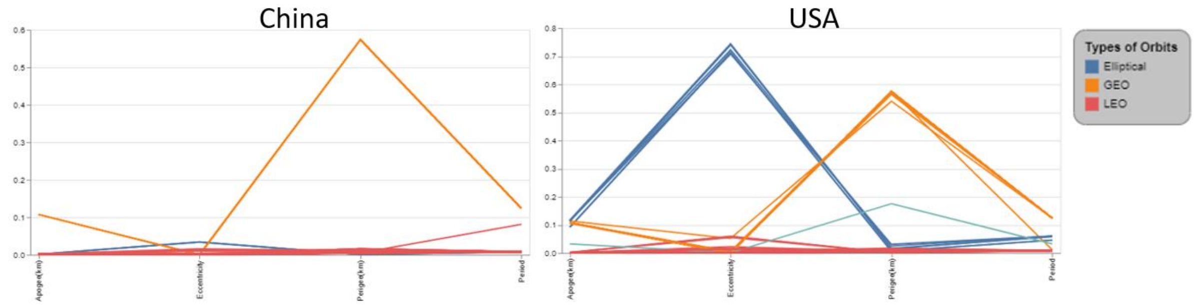

Figure 13. Earth Observation satellites used by China (left), USA (right)

FUTURE WORK

The UCS satellite database provides valuable insights that can be further explored by expanding our dashboard. We aim in our future work to probe the economic and political aspects of the satellite industry. By visualising these aspects, researchers and the public can gain a better understanding of the economic and political forces behind the industry. Additionally, visualising the data can help to identify potential areas for improvement and innovation, as well as potential areas of vulnerability. The project could have the potential to revolutionise the way we understand and interact with the satellite industry. By providing an easy-to-use, interactive tool for exploring and understanding the satellite industry, we can help inform and shape public policy decisions and research.

CONCLUSION

The UCS Satellite Database is an essential tool for understanding the current state of the space environment and for predicting future trends. This database provides a comprehensive and reliable source of information on the current activity of satellites and spacecraft in orbit around the Earth, as well as a platform for sharing information among various space agencies and research institutions. By combining data and visualisation, we can enable different users with different levels of expertise to better understand the complex interactions between satellites and their environment.

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