Data Sharing in Satellite Systems: Review of the Past and Opportunities in the age of large LEO constellations

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ABSTRACT

Since 1957, more than 14,000 satellites have been launched into space; 2022 marks a record year with the launch of 2,163 satellites [1]. The increased number of satellites in combination with technological advancements in satellite communications has enabled operators to collect vast amounts of science data and satellite telemetry. These large data sets can be utilized to ensure coexistence between the ever-increasing number of satellite systems, potentially reducing both the risk of harmful interference and in-orbit collisions. Additionally, they can act as decentralized information sources, improving our understanding of the space environment and increasing the reliability of satellites. Modern data sharing practices for space mission data can be categorized into either post-mission or real-time analysis. Post-mission analysis can lead to detecting anomalies that occurred during a mission by correlating data points from individual or different satellites. In contrast, real-time data sharing can also help avoid harmful communication interference events and in-orbit collisions. This paper provides a review of data collection and sharing practices across three types of satellite systems: university smallsat missions, federal government missions, and private sector/commercial missions. In this review and synthesis, the utility of those datasets is identified along with challenges associated with moving towards standard structures and stakeholder sharing practices.

INTRODUCTION

The number of satellites launched per year in the last decade has increased more than a factor of ten, with 2022 making a record year with 2,163 satellites launched [1]. Technological developments in satellite communications in combination with the increased number of satellites has caused the quantity of data collected from satellites to increase more than fifteen times over the past decade [2]. These large data sets available to operators can be utilized both to ensure the coexistence of satellites in orbit, but to also act as decentralized sources of information with satellites acting as sensors for the space environment. In addition, these data sets can help engineers and scientists better understand the impacts of space weather on satellites by characterizing anomalies and improving the overall system reliability. For such applications to be possible, telemetry data needs to be shared amongst operators and maintained in a format that can be accessed by researchers, engineers and satellite operators. Data sharing practices have been in place for years in organizations like NASA and NOAA, but in the age of large commercial constellations new data sharing methods need to be created that meet the needs of all stakeholders: industry, governments, international agencies, academia and the general public.

This paper provides a review of data storage and sharing practices in place today for satellite missions that can be categorized into either post-mission or real-time analysis. These data sharing practices are evaluated for three different types of satellite systems: university smallsat missions, federal government missions, and private sector/commercial missions. The utility of sharing telemetry data is also presented for the use cases of understanding the space environment, increasing the reliability of current and future satellites as well as ensuring the coexistence of satellites in space. This study identifies the challenges associated with satellite telemetry data sharing and the opportunities of making large satellite data sets available.

REVIEW OF DATA SHARING PRACTICES

Sharing of data from satellites can be categorized as either real-time or post-mission sharing. Each serves a different need. Real-time sharing is important for communicating critical information between systems to enable their seamless operation while post-mission sharing supports detailed analysis of systems and their performance. Post mission data sharing has been in place from the early days of space exploration with NASA making scientific data publicly available through repositories such as the Planetary Data System (PDS) [3]. In recent years and with the emergence of small satellites and university missions, more data sets have been made publicly available through a variety of channels but the lack of consistency between data formats and platforms makes it difficult to be utilized.

The rapid increase in launch rate of satellites has led to congested orbits and high demand for radiofrequency spectrum. These in turn have spawned the development of real-time data sharing techniques in areas such as collision avoidance and frequency coordination between satellites [4]. In 2021, the Federal Communication Commission (FCC) released a Notice of Proposed Rulemaking (NPRM) seeking comment on the impact and appropriate methodologies for the sharing of Non-Geostationary Satellite orbit (NGSO) spacecraft beam pointing information to help multiple networks coexist while utilizing the same frequency [5].

Sharing of satellite data presents confidentiality challenges due to the proprietary nature of the commercial companies and federal organizations. The level of confidentiality can be broken down to four categories based on the operator: Universities/research laboratories, civilian government agencies, commercial companies and defense agencies. The first three categories will be presented in the following subsections. Commercial companies tend to be protective of their data, although there are examples of data sharing mostly through partnerships with research institutions [6]. Commercial companies have also shared data in the past for monetary value or in exchange of services offered by a third party [7]. Civilian agencies like NASA and NOAA have robust data sharing systems as they are federally funded with a mandate to conduct research and share their findings with the public. Ground station networks like TinyGS and SatNOGS have made sharing of data from universities and research missions more accessible, though some groups using these platforms still keep their data confidential [8][9] .

University Satellite Mission Data

In June 2003, the first university cubesat was launched to orbit and by 2022 more than 800 cubesats had been launched by universities and research laboratories [10][11]. The cubesat platform lowered the cost of space-based science allowing students, faculty and researchers to test their payloads and designs. With the exponential growth in cubesats, there was a corresponding increase in the data collected in space. The data collected by satellite missions are handled differently based on the operator's experience and objectives.

Institutions with legacy cubesat programs, like University of Colorado at Boulder, have satellite data publicly available on their mission's webpage with different data product levels [12]. This creates a valuable repository for post mission data analysis of both the payload data and the system's telemetry. Some governmental and nongovernmental organizations that fund satellite missions require the data produced to be made publicly available. For example, the Planetary Society that funded the LightSail2 mission, built and operated by CalPoly San Luis Obispo, made the satellite's telemetry data publicly available [13]. Other university missions have their data available on github or other repositories that can be accessed by the public.

The large datasets produced by university satellites missions lack a centralized and standardized database making it hard for researchers to utilize this vast resource. Data might be publicly available, however, it is challenging to search each mission's website and identify whether a mission dataset exists. In addition, each mission stores their data in different formats which increases the data scraping and processing times.

Federal Agency Mission Data

Federal agencies such as NASA and NOAA have a long history of sharing satellite data collected in orbit. Data are either shared as raw telemetry/payload data or are directly incorporated in applications such as the NOAA space weather conditions dashboard [14].

NASA's PDS was established in 1989 in response to the threat of planetary data loss identified in 1982 [15]. The PDS has a long-term archive of digital data returned from NASA's planetary missions and serves scientists and engineers across the world [3]. The database is primarily for payload data from satellite missions, although satellite telemetry can also be found. It is managed by planetary scientists and NASA engineers to ensure the data are well documented and maintained. The PDS follows strict data standards with detailed documentation that need to be followed by all NASA funded missions and research activities. The PDS can serve as a model for data sharing systems for university missions to ensure data is not lost and accessible by the academic community as well as the industry.

NOAA has multiple databases with data from both their satellites and ground-based sensors. Thousands of datasets can be accessed through NOAA's OneStop data sharing platform [16]. Similarly, the PDS the datasets are primarily utilized for science payload data, with some satellite telemetry also available. The data can be accessed either directly through the webpage or after a request is submitted to NOAA. Some datasets like the Jason-3 telemetry data are restricted and thus not publicly available [17].

Federal agencies have robust data sharing systems when it comes to science data from satellite payloads. However, satellite telemetry data are still not widely available or are restricted from public access. Sharing of telemetry data from NASA and NOAA missions can not only have scientific benefits, but also act as a model for universities to create a CubeSat data-sharing framework.

Commercial databases

Commercial companies treat telemetry data confidentially. In the past, commercial companies have shared data with universities and academics that has led to scientific and engineering advancements [6]. Often companies, like planet labs, share payload data for monetary value with discounted pricing for academic institutions, however, telemetry data have not been monetized [7]. The value behind satellite telemetry data though has led to the creation of commercial databases that exist behind paywalls. These commercial databases have been used for research purposes providing insights for the space environment and satellite reliability [18][19].

Commercial companies seek to extract value from their payload and telemetry satellite data thus a public data sharing system would be challenging for commercial satellites. Alternative data sharing methods are being explored for this sector where operators can benefit from mutual data sharing to protect their satellites in orbit [20]. Such a system would require high confidentiality standards and the collaboration of multiple companies with aligned interests. Real-time data sharing that ensures the safe coexistence of a large number of satellites is of benefit to all spacecraft operators and could act as a first step towards commercial satellite data sharing [21].

Real-time data sharing

Real-time data sharing was first implemented by federal agencies and specifically NOAA to share weather information for both earth and space [22]. Weather phenomena progress in real time thus making the creation of an appropriate data sharing system necessary. Satellites from different federal agencies are equipped with sensors that are used to update predictive models of the magnetic field, solar wind and solar flux in real time. The NOAA space weather dashboard provides a summary of the predictions of such models as well as space effects warnings for satellites [23].

The congestion in orbits has created the need to better track satellites and space objects [1]. Different approaches have been taken to tackle this problem with companies like LeoLabs focusing on ground-based radars, while others like Slingshot Aerospace are focusing on a data sharing with the Slingshot Beacon, a cloud based data sharing and coordination platform in which operators share ephemeris positioning and planned maneuver data from their satellites [20][24]. The platform uses this data to calculate orbit projections and help companies protect their assets from in-orbit collisions. In addition to positioning, data operators can report environmental anomalies collecting valuable data points for space effects research.

The increased number of satellites in orbit has also created challenges in managing spectrum. The FCC through an NPRM is seeking comments on how data sharing can better facilitate interference coordination [5]. The Spectrum Access System (SAS) of the Citizens Broadband Radio Service (CBRS) is an example of how a real-time data sharing system can improve the utilization of radio frequency spectrum. The SAS is programmed to prevent interference by collecting data from the Environmental Sensing Capability (ESC) sensors to detect users with high priority. If one is detected, users with lower-priority licenses are automatically reallocated to a different part of the spectrum; i.e., the computer automatically switches the user's frequency to one that is not being used to prevent interference. To do this, each user must have a Commission-approved CBRS Device (CBSD), which acts as a base station in which users can transmit and receive signals that can be interfaced and controlled by the SAS [25].

UTILITY OF DATA SHARING

The analysis of satellite data in real time or post-mission has led to a better understanding of satellites and the space environment. The deployment of large satellite networks has created potential new data sources and their geographically diverse distribution makes them ideal for localizing phenomena such as atmospheric drag and micrometeoroid showers. These new data sources can also help minimize the challenges that arise from the coexistence of all these satellites in orbit. The vast amount of new data cannot be utilized though without a proper data sharing and storage system.

Space Environments and Effects Detection

Data from NOAA's and NASA's space weather monitoring satellites are analyzed and communicated through applications such as the OneStop data sharing platform [26]. In addition to dedicated sensors, satellite telemetry streams have been used to better understand space phenomena such as atmospheric drag [27]. Specifically, more accurate atmospheric drag models have been produced by assimilating GPS measurements and accelerometer data [28][29]. Atmospheric drag is highly dynamic and new mission design concepts such as satellite formation flying and precision maneuvering for in space servicing can benefit from higher fidelity atmospheric models that are updated in real time. Sharing telemetry and tracking data from commercial LEO satellites can allow the research community to produce such high-fidelity models. The viability of high precision atmospheric drag models has been demonstrated through a study carried out by the University of Colorado at Boulder using the tracking and attitude data from the SPIRE satellite constellation [30].

Satellite telemetry has been utilized in the past for characterizing the debris environment. Momentum and attitude data can be used to identify minor debris impacts on satellites and characterize the orbital debris environment [31]. Small debris and micrometeoroids under 1cm are considered untraceable and it is estimated that there are more than 130 million space objects between 1mm and 1cm [32]. Micro-debris impacts can result in satellite anomalies or in some cases complete loss of the satellite [33]. Utilizing the three-axis momentum data from telemetry streams and different filtering techniques, researchers have been able to detect and characterize impacts reliably down to 10 mg with 5 mg uncertainty [34]. In addition, research has been conducted on how debris impact detection on satellite constellations can help characterize the debris environment at a given orbit across time [35]. The same study proposes the creation of a debris impact data archive as a new means of cataloging debris data that is in accordance with the United States Space Policy Directive-3 [36].

The concept of using satellite telemetry as a sensor for detecting and understanding the space environment is not new, however, the new landscape of large LEO constellations creates opportunities for both researchers and the industry. The increased number of spatially diverse data points can allow the tracking of the space environment across time, informing operators of potential environmental threats to their system. For this to be achieved a robust data sharing system needs to be in place for the collection and storage of such data from different satellite operators.

Reliability of satellites

Estimating satellite failure rates is challenging as the prediction is only as good as the available data. The National Geophysical Data Center (NGDC) database that was in operation between the 1970s and 1992 recorded 5811 anomalies as reported by the satellite operators, with only 45% being diagnosed [37]. The Seradata SpaceTrack database is considered the most detailed with data from the early 1970s [10]. Unfortunately the later database requires a paid subscription and limited information is publicly available. From those limited information it is known that 2405 satellite anomalies are reported for the 1970s-mid-2012 time period and 866 small satellite from 40-500 kg have been tracked in the 1990-2019 timeframe [38][10]. From the small satellites tracked in SpaceTrack 37% have failed in orbit, with this value being aligned with a study conducted by NASA for the 2000-2016 time frame estimating an approximately 35% failure rate [39]. In both databases, the majority of failures are attributed to unknown factors and researchers have focused on better understanding the in-orbit satellite failure modes. A study authored by David Galvan on behalf of the National Defense Research Institute (RAND) highlights the need to create a database with locations, subsystems, and conditions under which anomalies have occurred in order to characterize those “unknown” anomalies [40].

The majority of known satellite failures are attributed to three categories: Unknown electrical, power and ADCS failures [18]. Studies have been conducted to understand the cause of those three failure categories, relying on satellite telemetry, reported anomalies and space weather reports [41]. To identify the failure origin, the degradation of components over time is tracked and the sub-system’s activity at the time of the failure is analyzed [42].

In an effort to characterize some of the unknown electrical failures, Stanford’s Space Environment and Satellite Systems Lab conducted a study in which a trend was identified between the flux of sporadic meteoroids and the number of electric anomalies [18]. In that study, telemetry data from the Jason 1 satellite were utilized to identify anomalous currents in the input of the payload and the output of the solar arrays during potential micrometeoroid impact times. A data sharing system with information from the large number of satellites currently in orbit could provide further insight on the effect of such micrometeoroid impacts and identify their geographical location in orbit.

A study conducted by the European Space Agency (ESA) using telemetry data of the Solar and Heliospheric Observatory (SOHO) observed the degradation of satellite components over the mission lifetime [43]. By monitoring the voltage and current output of the solar arrays a 2% per year degradation was observed that was within the 4% per year requirement, however, a strong correlation was observed between proton event and rapid solar array degradation. Documentation and sharing of such insights can help inform manufacturers and operators on how to increase the reliability of their satellite either by altering the design or the operating procedures during such proton events. Solar arrays were just one of the components that degrade over time with sun sensors and star trackers being affected. No observations or correlations were made between the degradation of the sensors and the space environment events, however, health data sharing could assist in understanding such phenomena.

In attitude stabilized satellites, the attitude control and determination system (ADCS) is a major driver of anomalies and failures with approximately 20% of satellite failures [44]. Anomalies in the Attitude Determination (AD) sensors as well as the reaction wheels can lead to cascading effects that result in a complete satellite failure. Sensor fault detection and filtering techniques have been critical in ensuring anomalies are isolated and don't result in reaction wheel maneuvers that can damage the satellite [45]. Other studies have focused on using telemetry data from the ADCS system to monitor the degradation level of reaction wheels and predict potential failures [46]. The ADCS health monitoring models are primarily developed using on ground accelerated-life testing that could be improved with space-based data if they were available.

The creation of data sharing practices and organized databases with satellite telemetry data can help researchers and engineers better understand the health status of satellites and explain the high percentage of unknown failure modes leading to new more robust system designs. The proprietary nature of satellite component data is a big challenge that needs to be overcome and a sharing system could only be achieved if there is bilateral benefit of all stakeholders.

Coexistence of satellite systems

In 2022, the number of active satellites reached a new record with 6905 active satellites [42]. Two major coexistence issues the satellite industry is trying to address are the satellite collision risk and radiofrequency spectrum interference. Specifically Kayhan Space, a satellite operator of just 50 satellites received approximately 300 official conjunction alerts per week [47]. In 2021, the FCC issued a Notice of Proposed Rulemaking (NPRM) on data sharing to improve real time radio frequency coordination [5].

The collision avoidance system in place as of May 2023 is primarily passive with radar and optical sensors of the 18th Space Control Squadron actively tracking more than 47,000 man-made objects and alerting satellite operators of potential close encounters with space debris or active satellites [48]. It is estimated that only approximately 3-4% of these alerts require operators to move their satellites to avoid collisions creating a need for developing better techniques to monitor and estimate collision risk [47]. Research studies on sharing tracking data for satellite collision avoidance have been published from the early 2000s before the rapid increase of orbiting satellites [49]. Commercial companies like LeoLabs and Slingshot Aerospace have also developed technologies for satellite tracking and data sharing for collision avoidance [24]. Real-time data sharing of tracking and GPS data is currently being demonstrated by Slingshot Aerospace's Beacon product, a service that will be expanded in the future to include additional information to serve more applications and needs.

The growing demand for satellite radio frequency spectrum necessitates data sharing among industry, government, and academia to enable an efficient use of such resources. The recent FCC NPRM that requested comments on data sharing for interference mitigation and frequency coordination has shown that maintaining a competitive advantage while sharing sensitive information is a delicate balance. Some companies, especially defense contractors, are hesitant to share sensitive data, while commercial users and public interest groups are supportive. Recommendations from satellite operators vary from mandatory sharing of operational data to limited requirements in cases of failed coordination efforts. The development of a definitive list of minimum shared information and methods of sharing is suggested by the Commission. Balancing the needs of different stakeholders and adapting to the evolving nature of the field are crucial considerations.

Confidentiality in data sharing

Confidentiality of shared data is one of the main challenges that hinders the development of large data sharing systems. The commercial world represents the vast majority of satellites in orbit, satellite telemetry and other measurements are considered to have intellectual property value and thus are marked as proprietary. Data points from the satellite payload, sensor outputs and system performance are the most critical in identifying failures and sensing the space environment, however, they are also the measurements operators are least willing to share. Figure 1 presents different categories of data and ranks them based on their helpfulness for satellite reliability purposes (upwards) and the willingness of operators to share such data (downwords) [50].

Data trusts have been used in a number of industries to solve the challenges that arise from sharing confidential information between different parties. Data trusts are a framework to share data on behalf of individuals and organizations. Trusts are built on shared cloud or on-premise data infrastructure, held by the third party, and use audit logging to track individual or organizational changes to the data [51]. The third party maintains security over the data and access permissions so companies can remain confident as they upload data to the trust.

A data trust solution could benefit commercial and federal operators that wish to contribute to scientific and engineering developments with their data, but want to make sure confidentiality is maintained. Within the trust, stakeholders have access to crucial mission telemetry and reports from their peers, utilizing this shared intelligence to refine their satellite systems by improving their reliability and increasing the available space environment data points. Established federal organizations such as NASA and NOAA can act as the trusted third-party of such an effort to inspire confidence in operators willing to share their data.

CONCLUSION

To summarize, data sharing practices have been in place for years through systems established by NASA and NOAA or direct collaboration with researchers. The data sharing practices have been primarily for science payload data although in recent years commercial databases have been in development with satellite health and telemetry data. The utility of satellite telemetry in better understanding the space environment and satellite reliability has already been demonstrated by researchers with numerous studies. Recently data sharing of telemetry data has also been explored for applications that can ensure the coexistence of satellite networks. The new diverse data sources of the large LEO constellations that are often geographically evenly distributed blanketing the earth are an opportunity for researchers and engineers. These new data sources can lead to the development of more accurate space weather models, understanding satellite anomalies, supporting the coexistence of satellites in congested orbits and the sharing of the limited radiofrequency spectrum. University, federally funded and commercial missions use different techniques to store and share their data making their use challenging. For the vast amounts of data collected to be accessible, a data sharing and storage framework needs to be developed to ensure the usability of data. The NASA PDS system has strict data structure rules and a dedicated team to maintain data, serves as an example on which a new telemetry data-sharing system can be built. For commercial operators to participate in such an effort the confidentiality of certain data will have to be maintained with data trusts being a potential solution.

Figure 1: Satellite data categories ranked based on helpfulness in mission failure detection and willingness to share

Further studies need to be performed with available satellite data to identify the key metrics for each application. The collection of some specific metrics from multiple satellite systems can be a starting point in developing data sharing and storage frameworks. In addition, further consideration shall be given on the possibility of an existing data sharing platform to accommodate telemetry data, at least for university and federal missions that can be made publicly available.

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