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Integrating Artificial Intelligence with Space-Based ADS-B for Next-Generation Space Traffic Management

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Abstract: This paper explores into the concept of space traffic management using current aircraft navigation and surveillance systems such as ADS-B technologies, along with artificial intelligence (AI). This paper conducts a feasibility study on the use of present ADS-B systems that are modified for space flight and satellite surveillance. The scope of the paper focuses on mainly the surveillance of commercial space flights, as well as sub-orbital space vehicles (such as reusable launch vehicles, satellites in low earth orbit (LEO), etc.), and the potential safety hazards that can be posed. The objective of this study is to build a model to manage space traffic along with commercial air traffic simultaneously, while also focusing on tracking and guiding space traffic, to ensure safe operations. A conceptual view of the model, along with the introduction of ADS-B, how it works and the integration of it, with AI, potential limitations and hazards that can occur and possible solutions to these are explained, and recommendations for future studies is also mentioned. The proposed idea could use the help of the current trends of AI and Machine Learning that will be instrumental in the future for making such models more efficient, reliable and safer. Hence, this paper explores the idea of AI-enhanced ADS-B Systems for Space Traffic. By using AI and Machine Learning to optimize the efficiency of ADS-B, it was found that anomalies could be easily detected quicker [1], safety could be improved, analysis of flight path regions could be automated, etc.

Table of Contents

1. Introduction

In recent decades, the world has shown a keen interest in the exploration of space, which is still at large, a widely unexplored domain. From inter-planetary exploratory missions to satellite deployments and recently, space tourism flights, Humans have kept pushing the boundaries further and further. This in turn has pushed forth the growing need for spaceflights for both commercial and non-commercial purposes. In the recent years, we have seen several well-known companies venture into the lucrative business of space travel such as Virgin Galactic and Blue Origin, which provide spaceflight for commercial purposes. It is further expected that more companies will invest and grow their presence in the spaceflight sector. This is more evident considering the projected market value of the spaceflight sector in 2032 as 12.95 Billion USD from 827 Million USD in 2023. With improved safety, due to technological advancements, as well as more feasibility in recent times, the interest in spaceflights as well as sub-orbital spaceflights has grown massively. [2] With the growing demand for space flight and civilian space tours, along with the sharp increase in number of spacecraft and satellites being launched. As space exploration and commercialization continue to push further frontiers forward, there is an increasing need for effective and reliable monitoring and tracking of spacecraft. An example to show the growing need for monitoring and surveillance of spacecraft and satellites is the 2009 Iridium 33 and Cosmos 2251 Collision, resulting in the most accidental fragmentation in record. With the growing number of launches every year, the chances of collision and the debris caused by it, will be dominant [3].

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Figure 1. Spaceflight growth [2]

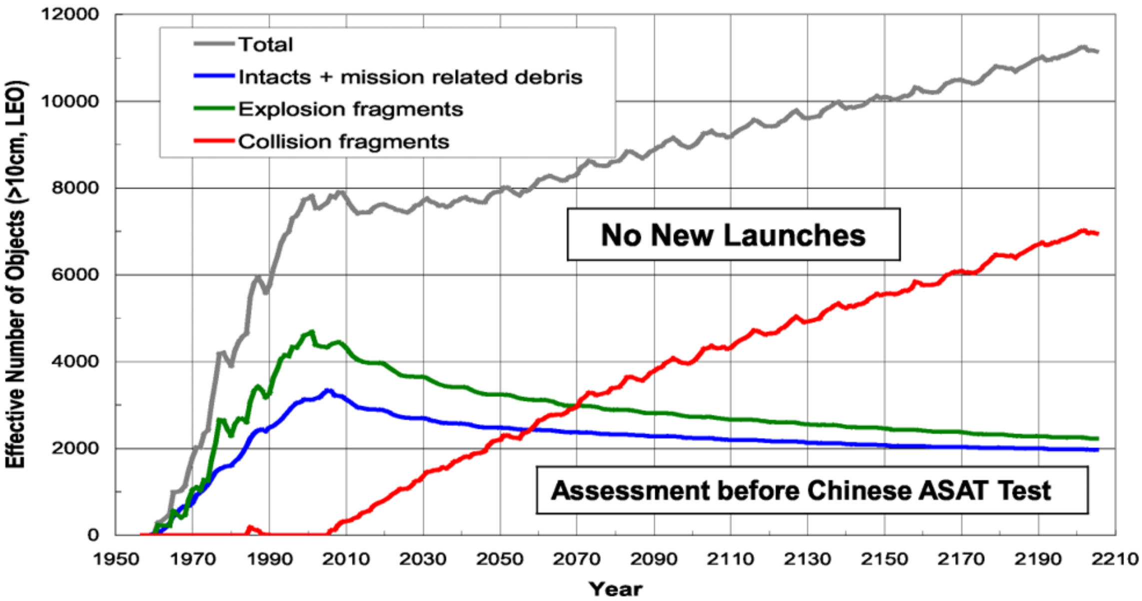

Figure 2: Potential Debris in LEO in the future [3]

Hence, these collisions and accidents can be prevented with the use of real-time surveillance and navigation tools. One of such tools is the ADS-B. The Automatic Dependent Surveillance-Broadcast (ADS-B), well used in the aviation sector, has tremendous capabilities to revolutionize the control and monitoring of traffic in space. It can provide with precise navigational capabilities and also provide real time data such as speed, altitude, location proximity, etc. There have been research into the usage of ADS-B for commercial space flight but in this paper, we look at the optimization of ADS-B for spaceflights and spacecraft using AI and Machine Learning, to improve its efficiency.

2. Literature Review

ADS-B systems were traditionally made for surveillance of air traffic and to assist air traffic controllers, or ATCs, in helping navigate aircrafts across airspaces. It was crucial for the safety of the vast number of aircraft flying across the world. It uses ground stations to receive transmissions from aircraft which include its position, altitude, airspeed, identification, etc. this information are then routed to the control tower. ADS-B has been particularly helpful to controllers especially in remote areas with limited radar coverage. Traditionally, ADS-B systems are used for aircraft surveillance, be it civil or general or military. Furthermore, it is primarily used as a tool that aids controllers in navigating aircraft in airspaces more efficiently.

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As an extension to Ground Based ADS-B stations and systems, more research was done in extending ADS-B into space. While traditional ADS-B Systems can provide further coverage of aircraft surveillance, it still depends much on the topography of an area and the altitude of the aircraft. In certain areas with a higher elevation, aircrafts will need to fly at higher altitudes for ground based ADS-B systems to provide full coverage. Hence, to solve this, space-based ADS-B systems were conceptualized as a fix to these issues.

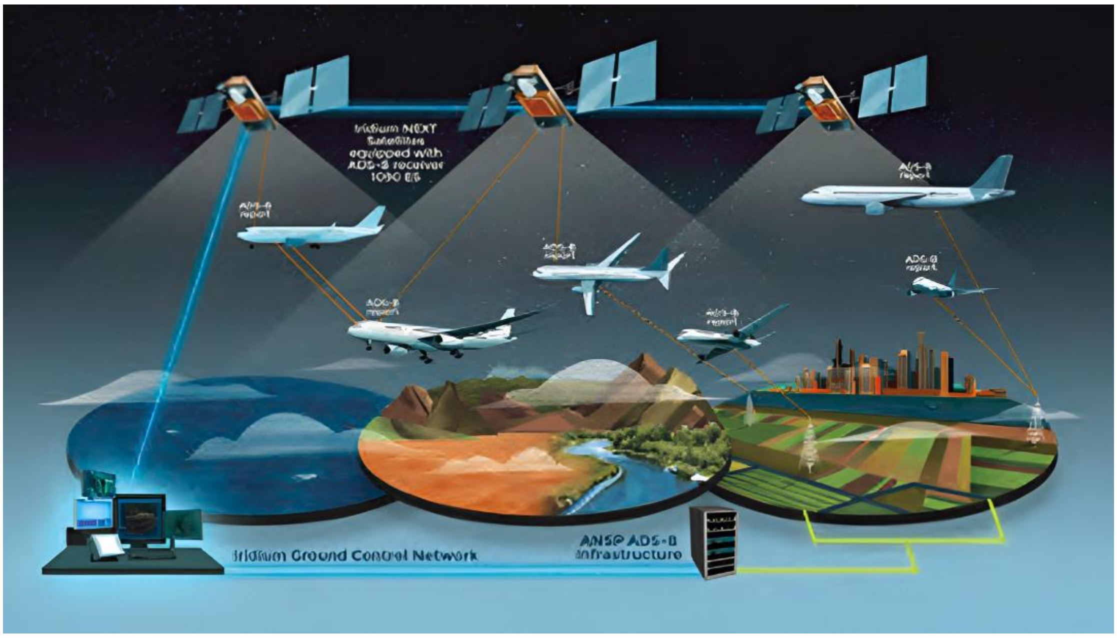

Figure 3: Space Based ADS-B System [4]

In a space-based ADS-B system, it uses the help of Low Earth Orbit (LEO) Satellites that act as ADS-B Stations and hence can cover more area and transmit data quicker for controllers to see. This concept can also be further extended for spaceflight as high altitude flights and even LEO traffic as well [4]. Meanwhile, Artificial Intelligence (AI) is used widely in advancing many sectors including aerospace and space sectors. It is widely used in navigation of satellites, guidance and control of space vehicles, data transmission, and many more. The uses of AI could be very useful in advancing GNC (Guidance, Navigation, and Control) of satellites or other space vehicles as well as to help air traffic controllers on managing a large number of aircraft in a given airspace, more efficiently, especially at busy airspaces. While there have been research into Space Based ADS-B systems, for both air and space traffic, as well as research into the use of AI in managing and monitoring such traffic, this paper primarily addresses the possibility of having both: space-based ADS-B systems and AI, together which, can enhance and improve the working efficiency of air and space traffic.

3. Space-based ADS-B System

ADS-B has been generally used for either General Aviation (GA) or for high performing aircraft and military aircraft. These are operated on different frequencies. ADS-B operates similar to SSR (Secondary Surveillance Radar) with the difference being SSR using Radar Beacons and ADS-B using its own function. In recent times, there has been more for TCAS (Traffic Collision Avoidance System) development in regard to ADS-B, with the introduction and implementation of a limited bandwidth, enhanced version of existing Mode-S Transponder, which is used Avoidance System) currently. Currently, Ground Based ADS-B Systems are more predominant. These require ADS-B Ground Stations to receive data from aircraft and send them to control towers. ADS-B uses either UAT (or Universal Access Transceiver) which is applicable to all airspaces excluding Class A airspace, and Extended Squitter, which operates on a special frequency of 1090 MHz [5]. However, the issues with ground based ADS-B systems, such as range, topographical challenges, limit the operational efficiency of ground based ADS-B systems. To resolve this, Space Based ADS-B systems were conceptualized and introduced. These work with the help of LEO satellites that provide better coverage and quicker data transmissions. Also, the space based ADS-B not only limits itself to the airliners but also shows that there is potential room for an enhanced and advanced ADS-B system that can be potentially applied to the space domain.[6][(Duan & Rankin, 2010)].

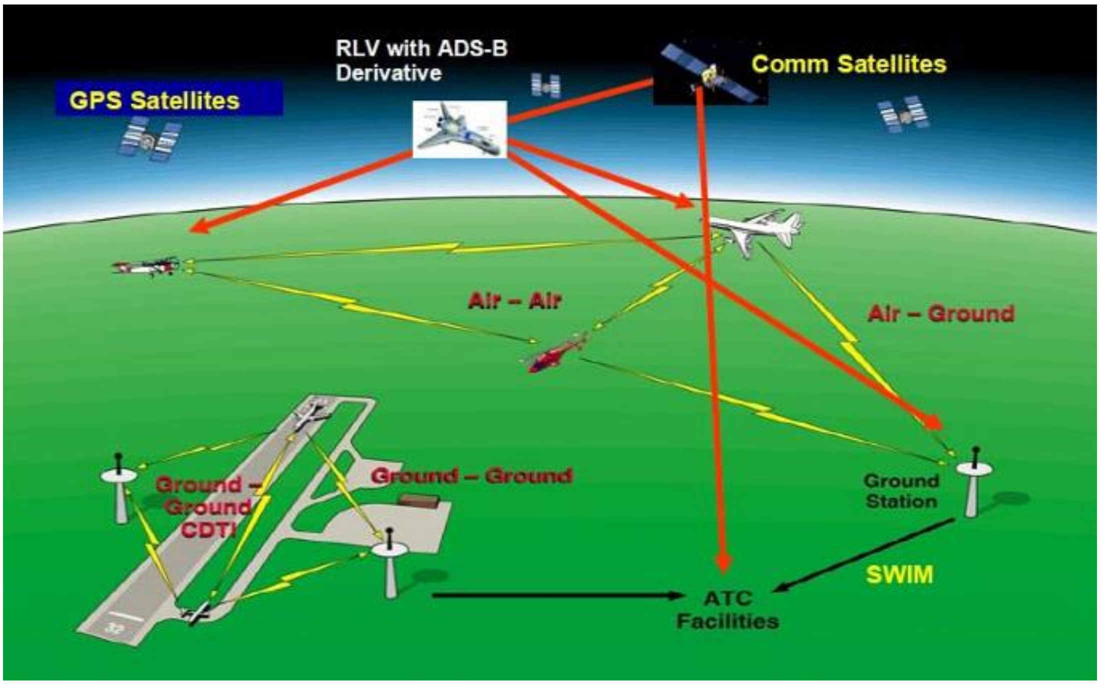

Figure 4. Enhanced ADS-B Concept [6]

Using System-Wide Information Management Network, we can share data and also use it to support SATM system [7] (Hayes, Birr, & VanSuetendael, 2008). SWIM operates over an interoperable (runtime) infrastructure (ground/ground and air/ground) through which the data and information will be distributed [8]. This in turn, can help us share real time data such as optimized flight routes, potential hazards, trajectory path, etc. using the DST Tool. [9] (Murray & VanSuetendael, 2006). DSTs provide recommended solutions or methods to evaluate potential solutions before implementation to system users such as, Controllers, Technical Operations staff members, etc. [10]. However, there are some technical challenges faced in space-based ADS-B systems. For instance, there might be a delay in relaying data (or data latency) as data has to travel from the GNSS onboard the aircraft to the satellite and finally to the ATC via ground stations. This latency causes the system to be inefficient as in airspaces with heavy traffic, it limits the efficiency of traffic management and moreover, fails to provide real time data of aircraft. In addition, Space Based ADS-B systems are also inefficient in relaying data of Low Altitude Flying Aircraft, such as after takeoff, due to lower signal strength. Finally, the existing ITAR (or International Traffic in Arms Regulation) regulations in the USA restrict the export or sharing of space technology including space-based ADS-B systems. This could hinder global cooperation in this technology being shared and operated across the world.

Artificial Intelligence in Space and Air Traffic Management

Artificial Intelligence is being used in several fields to improve efficiency, as well as to provide better results. This also applies to data management, where AI can help manage complex real time data such as the data received from aircraft and spacecraft in real time and process them. AI improves efficiency by reducing cost and time required to manage and process data. Models such as SVM (or Support Vector Machine), which use hyper-planes to segregate small and organized data, or Random Forest, which is a model that creates several branches of decisions and combines each output to provide better accuracy for large, unhandled data, are currently available AI models that handle data. These models help in calculating aircraft trajectory, finding faults within airframe, aerodynamic modelling, etc.

Companies like Blue Origin, SpaceX, etc. use AI in their space programs. Blue Origin use AI for predictive maintenance of their spacecraft and for real-time IoT (Internet of Things) insights and data. They have also adapted AI Technologies for reusable rockets.[11]. Meanwhile, SpaceX uses AI in their collision avoidance system for their satellites, under their space safety service. In addition, SpaceX's Starlink, which is a network of satellites, use AI to calculate the best route for navigating amidst debris and other obstacles. [12] These are instances of real-world applications of AI in the space industry. AI can hence support a wide range of applications and areas such as safety, autonomy, and real-time decision making, to name a few.

AI helps in predictive maintenance of airframes while also detecting structural anomalies during maintenance of aircraft. It also can improve the present collision avoidance systems by using real-time data, which it analyses

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and provides Decision Support Systems that aid controllers in managing air traffic, as well as, supporting autonomous capabilities in Navigation, Surveillance, and even in Autonomous flight capabilities.

Integration of AI with ADS-B for Space Applications

The possible integration of AI into Space-Based ADS-B system for monitoring space debris as well as ensuring safe orbit or travel of satellites and spacecraft, is feasible. It operate with an in-built algorithm that uses state-of-the-art systems such as TCAS (in aircrafts), SONAR, etc. that can be modified for space applications. With these systems, the AI algorithm can simultaneously manage traffic within a localized area. The Inclusion of ADS-B further provides key data such as acceleration, direction, projected trajectory or orbit, etc. This data can be then fed into the AI algorithm which receives these inputs and organizes them using complex models and algorithms like SVMs. The organized data in the hands of AI, further improves the efficient management of the model. The data transmission can occur through dedicated networks or pathways, such as NASA's SCaN program. The AI Model assess the data received and prepares the optimal path to follow and relays this back to the satellite or spacecraft. In addition, this data can also be sent to the ground-based control centers for crucial space missions. This further helps space missions occur more safely.

Hence, the integrated model can be of great use and could make space travel safer.

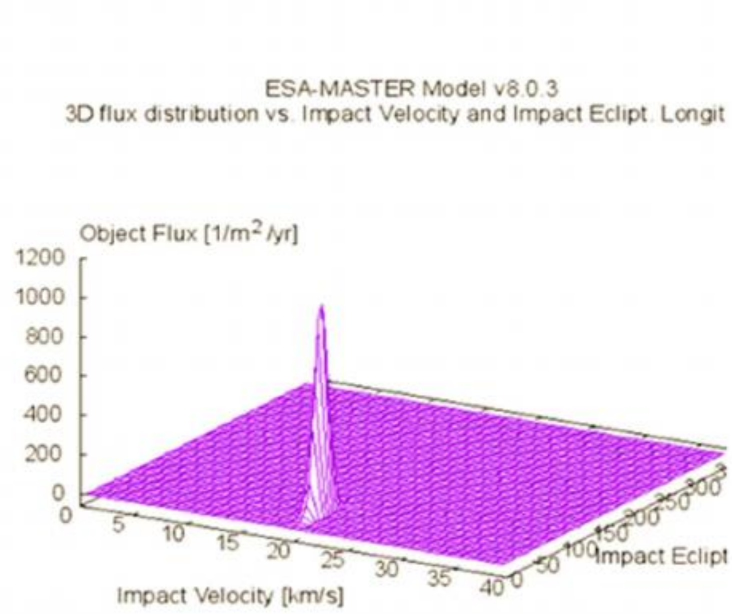

Figure 5. Velocity and Impact of debris on objects in LEO orbit. [13]

This is important, as with the rise in number of launches and space flights rising reach year, the need to monitor, track, and manage them efficiently, as well as safely, also increases. Hence, with the proposed Enhanced ADS-B System, this can be managed easily. However, ADS-B technology has some drawbacks and limitations. These include Data Message limitations (especially UAT Messages) after 101,300 feet, less stringent data latency rules that need to be more stringent for space travel, ITAR Limitations on GPS and the effects of this on ADS-B Data, and other technical issues.

4. Technical Challenges and Limitations

4.1 Hardware and Infrastructures

One of the biggest challenges for the idea of space based ADS-B system would be the need to retrofit satellites, as currently, satellites are not designed to be fitted with ADS-B systems or it's components on board. Hence, there will be a need to design new satellites that can accommodate the ADS-B Components within satellites or space vehicles as such. Another issue is the lack of ADS-B infrastructure on the ground, such as ground station networks, etc. Moreover, the concept of an entirely space based ADS-B system, without the need for any ground-based equipment, requires extensive testing in the harsh space conditions, to be deemed reliable.

4.2 Range and Latency

Another issue is the range of ADS-B Systems. Satellites and other space vehicles fly or hover at extreme distances apart from each other. This necessitates an extended range for a space-based ADS-B system. In addition, obstacles such as debris, meteors, or the earth, can block the line-of-sight of ADS-B transmission and receiving signals, which can further reduce its reliability as a safe means of traffic management. Moreover, the ADS-B data being sent over long distances between spacecraft/satellites should have low latency. With these space vehicles moving at extremely high speeds, it is essential to have low latency to effectively and safely manage them across long distances.

4.3 Other Considerations

There are other considerations to be considered while developing AI Space-Based ADS-B systems. With the added ADS-B Transponders and Receivers, the additional weight requires more fuel for the spacecraft to continue its journey. In addition, Additional Power also needed to be supplied to the ADS-B Components for its continued usage. While AI has proven to effectively manage traffic, there has to be additional focus placed on the maneuverability of the spacecraft or satellite after the advisory sent by the AI enhanced ADS-B System.

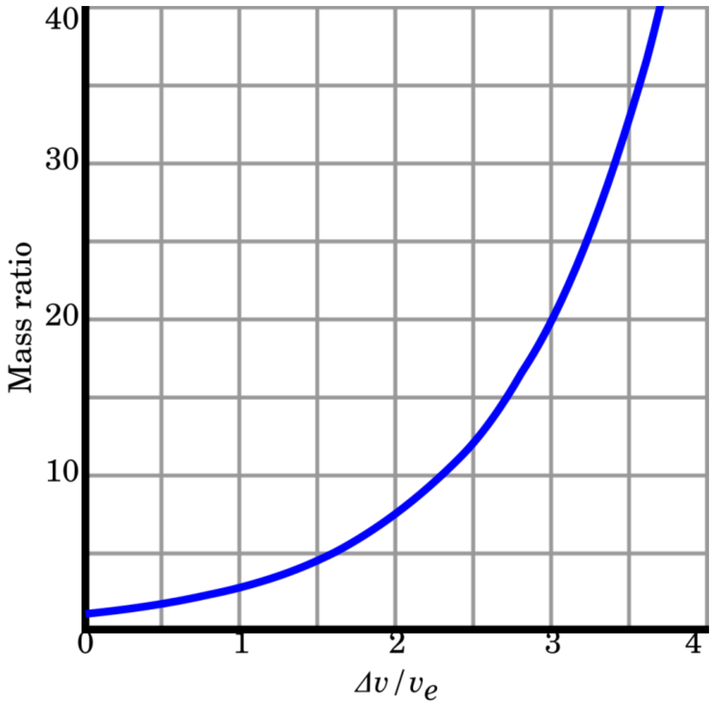

Fig 6: Graph between Mass Ratio and Effective Exhaust Velocity Ratio [14]

Furthermore, such additions increase the overall cost of the space programs as well as launch costs and operational costs. The inclusion of such sophisticated equipment requires more careful maintenance, and the AI system requires well trained scenarios to be prepared for real time management. In certain Low Earth Orbit vehicles, the increased weight along with the present atmospheric drag, affects the aerodynamic aspect of the spacecraft by inducing more drag and harming it's fuel efficiency. The inclusion of external antennas for transponding and receiving signals can also contribute to the above.

5. Discussion

As we have outlined the technical challenges of the proposed AI-Based Space based ADS-B system, we shall now look into the feasibility and scalability aspects of the model. Space Based ADS-B systems have already been introduced and are widely being researched upon. It is looked upon as one of the options to explore, to solve the limitations of currently operational ground-based ADS-B system. An example for this is the GATOSS (or Global Air Traffic Awareness and Optimization through Space Based Surveillance) project, a space-based ADS-B project that studied on whether ADS-B systems could be applied on a space domain and the technical feasibility of the concept of space based ADS-B system. The findings in the project show that ADS-B signals were successfully received from Low Earth Orbit (LEO) satellites, thus showing that, space-based ADS-B system is a feasible concept. [15](Bjarke Gosvig Knudsen, 2014)

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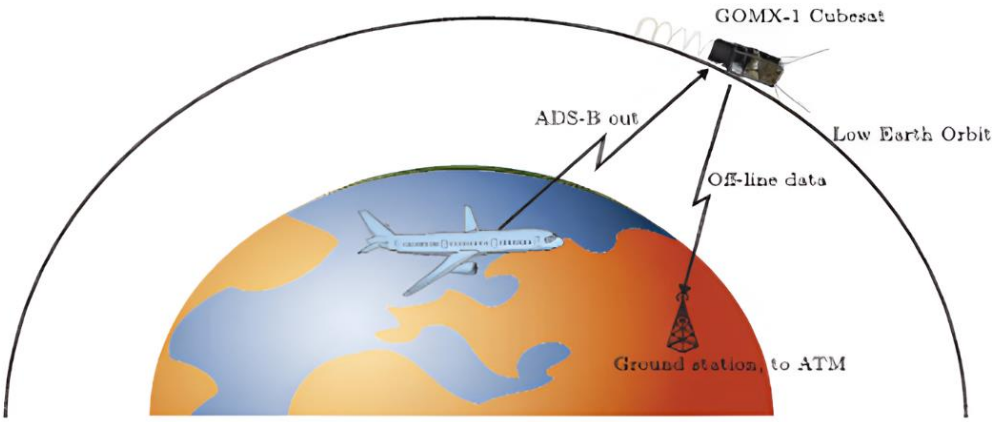

Fig 7: GATOSS Satellite (formerly called GOMX-1) and the Space Based ADS-B system [15]

Also, Artificial Intelligence (AI) is playing a key part in autonomous Space Traffic Management (STM) and Collision Avoidance systems. With AI now trained to process and handle large amount of complex data in real time and advancements in predictive modelling, the increasing use of AI in Space companies such as SpaceX, Blue Origin, NASA, ESA, etc. is widely seen. For instance, the European Space Agency (or ESA), is planning a project on an automated collision avoidance system, which will use Machine Learning and AI to assess the risk of colliding with space debris in real time [16].The proposed system requires the model to be adapted in all spacecraft and satellites to be efficient and successful. This requires the retrofitting of existing satellites or spacecraft that do not have the equipment to transmit or receive ADS-B signals and data. Also, all newly built and future spacecraft will need design changes to include the equipment such as antennas for signal communications, Mode S Transponders and receivers, etc. In addition, the scalability of existing AI models to handle such large, complex data in real time, with very less latency is crucial. For this, AI models needs to be trained well with test data, similar to the real life ADS-B data, to establish a well set framework for the working of the proposed system.

While the current space traffic management systems use primary data sources and include Ground Based Radar or Telescope, Space Based Radar, Sensors, etc. the proposed system shall rather include space based ADS-B system that includes better optimized sensors, transponders for communication, AI driven data management and data fusion of real time data such as altitude, speed, etc. The setbacks with the current Radar and optical systems include fixed threshold and object size, which varies depending on Low Earth Orbit (LEO) or GEO. In addition, current systems cannot handle a large amount of objects to track at the same time and has a high latency rate, and less precision in tracking debris and objects in real time [17]. On the other hand, the proposed AI with ADS-B system for Space Traffic Management promises an extended range of debris and spacecraft, can easily track a larger number of targets and objects, has lower latency and higher precision.

The proposed system has an abundance of benefits for Space Traffic Management (STM). The proposed system provides a global coverage with the added benefit of real-time traffic management across the area of coverage, using the help of AI models trained for this purpose. The increased coverage area also means that the proposed system shall be able to track more foreign objects or debris, beyond the scope of existing space ADS-B systems. With the safer environment for satellites and spacecraft to move across, the proposed system ensures the efficiency and safety of space travel, while also preventing any further debris build-up from future accidents between satellites/spacecraft. This is in-line with the efforts from organizations such as the United Nations (UN) to mitigate the build-up and risks associated with space debris build-up and ways to resolve them [18]. In addition, with fewer incidents in space, more space missions and space flights will be successful in their missions or flights, hence resulting in more scientific pursuits and better successes in them, leading to newer discoveries in science and space, while having less economic losses, in the form of crashes or incidents, leading to the mission failure.

However, the proposed system also has certain risks, that need to be considered before it's envisioning. The proposed system required a lot of changes in the designs of satellites, both existing and future ones, resulting in more spending. There is also the need for every nation and company to agree and be part of this system; to enhance it's efficient working. In addition, the complex data handling processes with real time data and real time decisions mean that there is no room for error and the AI models responsible for the decision making need to be very well trained and highly precise. Also, the additional technical challenges of working of the proposed system in the space environment, where the factors existing vary greatly from Earth, needs to be addressed, like radiation in space for instance [19].

The proposed system also provides strategic value to the various sectors within space, such as space tourism, debris avoidance, commercial missions and operations, etc. The proposed system makes space traffic safer and reliable, by minimizing risks and collisions. This promotes space tourism's safety and assures clients and passengers who opt to experience space tourism that it is safe and builds confidence within them, thus leading to more customers for space tourism companies. In addition, the proposed system should provide real-time data and organize them by priority while also predicting projected paths to avoid collisions with debris, to advance the current models of debris avoidance, in Space Traffic Management (STM). Finally, the proposed system helps commercial missions to avoid losses and additional costs by avoiding impact from debris, hence improving profits and success of the mission.

6. Future Recommendations

The proposed system can be further improved in the future by improving the critical thinking ability of AI to make real time judgments and decisions, without the need for intervention by humans, to fully automate the process. In addition, the model can also take further data into consideration, such as anomalies in real time environment, changes in surrounding conditions, etc. The proposed system can also include newer technologies in the future, to improve the efficiency of the model by addressing it's limitations such as latency, data management, etc. Small scale testing of the models before wide scale implementation should also be considered while efforts to bolster international cooperation on the project and international acceptance to contribute and use the system could also be discussed. Finally, newer strategies and ideas to improve long term sustainability and lowering costs can also be explored.

7. Conclusion

In summary, it is clear that the current systems of ADS-B or Space based ADS-B are not ready to be adapted to Space Traffic Management alone. However, with the rapid improvement of AI's capabilities, the combination of Space based ADS-B and AI, can prove to be a game changer in space traffic management and also in managing debris avoidance and detection, hence resulting in various benefits such as reduced costs, better safety and a safer environment for all spacecraft and satellites to travel.

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9. Conflict of Interest

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