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Assessing the True Extent of Dual-Use Potential in Satellites Through a Spectrum-Based Classification Model

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Abstract

This thesis explores the growing intersection between civil and military space activities by investigating the concept of dual use in satellites.

These systems can serve both commercial and defense purposes. The aim is to move beyond the traditional binary distinction between civil and military missions, by developing a model capable of measuring and classifying the degree of dual use in existing satellite systems.

To achieve this, a spectrum-based model was designed through the creation of a Dual-Use Index which allows to estimate the real dual-use potential of a satellite. After defining the problem and reviewing the current policy framework, the typical features of military satellites were analyzed as a benchmark. Based on this analysis, several dimensions were selected to build the index, considering both technical and organizational factors (such as the operator, primary user, mission purpose, sensors and orbital characteristics). Each dimension includes multiple subcategories, each assigned a specific score according to its strategic potential, and a weight reflecting its relative importance in the final formula.

The study analyzed satellites launched between 2000 and 2024, resulting in a manually filled Excel dataset, compiled using open-source information from official databases, where each satellite is associated with a final index score ranging from 0 (purely civil) to 1 (purely military), with 0.5 representing perfect dual use.

The results indicate that dual-use characteristics are increasingly common, especially with the rise of mega-constellations and the ongoing commercialization of space, where satellites often serve multiple strategic and civil purposes rather than fitting precisely into a single category.

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Acronyms

ESA

European Space Agency

NASA

National Aeronautics and Space Administration

EUMETSAT

European Organisation for the Exploitation of Meteorological Satellites

WMO

World Meteorological Organization

JAXA

Japan Aerospace Exploration Agency

USGS

United States Geological Survey

DoD

United States Department of Defense

PLA

People's Liberation Army

GPS

Global Positioning System

Galileo

European Global Navigation Satellite System

GLONASS	Global Navigation Satellite System (Russia)
PRS	Public Regulated Service
EO	Earth Observation
SAR	Synthetic Aperture Radar
SSO	Sun-Synchronous Orbit
SWH	Significant Wave Height
NDBC	National Data Buoy Center
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
GEO	Geostationary Orbit
HEO	Highly Elliptical Orbit
PNT	Positioning, Navigation and Timing
MTCR	Missile Technology Control Regime

ITAR
International Traffic in Arms Regulations

UCS
Union of Concerned Scientists

CMEMS
Copernicus Marine Environment Monitoring Service

Chapter 1

Introduction

Over the last twenty years, the space sector has changed deeply. Once clearly dominated by governmental programs, it has evolved into an hybrid environment where the boundaries between public and private, civil and military are increasingly blurred. The rise of commercial actors and the progressive diffusion of the New Space Economy have accelerated this transition, introducing new models of cooperation and competition that involve both state and non-state entities.
Satellites are no longer conceived as instruments for a single and well-defined purpose, but rather as flexible assets designed for multiple objectives at once: economical and strategic.

Within this context, the concept of dual use has become a central analytical key to understand the modern space landscape. Many satellites, even those formally designed for civil or commercial functions, can simultaneously enable military or intelligence activities, supporting surveillance, communication or navigation in operational contexts. This coexistence of purposes challenges the traditional binary classification that separates civil from military missions and reveals the need for a new interpretative and analytical framework capable of capturing the real spectrum of uses and interconnections among actors.

However, despite its importance, the notion of dual use remains ambiguous and underdefined, both conceptually and legally. International law still struggles to provide a clear and universally accepted definition, while existing policy instruments were conceived for a technological and geopolitical environment very different from today's one.
Treaties such as the Outer Space Treaty or export control regimes like the MTCR, ITAR and Wassenaar Arrangement attempt to regulate technologies with potential military implications, but their structure and scope are no longer adequate to address the complexity of contemporary satellite systems. The growing role of

private companies, the multiplication of public–private partnerships and the emergence of mega-constellations create new forms of interdependence that traditional frameworks fail to regulate effectively.
Furthermore, technological innovations such as artificial intelligence or responsive launch capabilities are reshaping the dual-use debate, introducing challenges related to data governance, transparency and accountability in space operations.

Against this background, this thesis aims to develop a new quantitative approach to assess and classify the dual-use potential of satellite systems.
The central idea is to move beyond purely qualitative or legal interpretations and to introduce a measurable model that represents dual use as a spectrum rather than a dichotomy. The goal is therefore to quantify, through a combination of technical and organizational parameters, how "dual" a satellite effectively is. This not only in its declared mission, but in its design and operational flexibility.
To do so, the research introduces a Dual-Use Index, a composite indicator that aggregates multiple dimensions reflecting the degree of strategic repurposability of a satellite, ranging from purely civilian (0) to fully military (1).

The structure of the thesis follows a logical progression that moves from the theoretical to the empirical. After this introductory overview, **Chapter 2** lays the conceptual foundation by defining what dual use means in general terms and how the concept has evolved over time. It explores its origins in international security and trade law and then extends the discussion to the space domain, showing through concrete case examples how these systems have become emblematic of the dual-use phenomenon. The chapter concludes by highlighting how emerging technologies are further intensifying this overlap and making regulation increasingly complex.
Chapter 3 deepens this reflection by addressing the regulatory and policy dimension. It examines the main legal instruments currently in force and demonstrates why they are no longer sufficient to manage the dual-use challenges of today's space environment. By analyzing the ambiguities and limitations of the Outer Space Treaty and of export control regimes such as MTCR, ITAR and Wassenaar, the chapter exposes the structural gaps that prevent effective governance. It also discusses new emerging issues, such as the unclear responsibility of private actors and the difficulty of distinguishing civilian from military infrastructures during crises or armed conflicts, thus framing the broader problem that motivates the need for a new classification model.
Chapter 4 introduces the methodological framework that guides the research. It explains how the model was conceived, starting from the definition of what constitutes a military satellite and identifying its characteristic features, which are then used as benchmarks for comparison. The chapter details how the work was

carried out: from data collection to the selection of the analytical dimensions that describe the satellites' technical and organizational attributes. It also illustrates how qualitative traits were translated into quantitative values and how each parameter contributes to the overall evaluation.

Building upon this foundation, **Chapter 5** provides an extensive description of each dimension included in the model. For every parameter the chapter defines the subcategories, their conceptual meaning and their assigned scores along the 0–1 scale. This part establishes the interpretative consistency of the index and clarifies the rationale behind the scoring system.

In **Chapter 6**, the various components are integrated into the final analytical framework: the Dual-Use Index. The chapter presents the weighting scheme that determines the relative importance of each dimension, leading to the final formula of the index. It then applies the model to selected satellite cases using real data from the compiled Excel database. Through practical tables and detailed examples the chapter shows how differences in configuration, ownership and purpose translate into distinct index values.

Chapter 7 extends the analysis to the entire dataset of satellites launched between 2000 and 2024, using statistical modeling and graphical visualization to identify macro-trends over time. The chapter for example, explores the temporal evolution of dual-use characteristics and the regional differences among major space actors.

Finally, **Chapter 8** draws the main conclusions and outlines the limitations of the study. It summarizes the theoretical and practical contributions of the research, emphasizing how the proposed model provides a structured and adaptable framework for assessing dual-use potential.

Chapter 2

Definition of Dual-Use

Before any technology or activity can be properly regulated, it is important to agree on a clear and shared definition. However, in international law, some key concepts are still hard to define universally and a big example of that is the case of dual-use goods.
Even though many international rules and agreements try to manage dual-use technologies, the term itself remains still unclear. This lack of clarity creates challenges for both legal systems and policymakers. Still, many countries have reached a common understanding through the definitions and approaches found in existing treaties and export control regimes.
This section introduces how the idea of dual use was first developed and how it has been interpreted in different areas over time, setting the stage for its later application to the space sector. [1]

2.1 Historical Origins of The Concept

Even though dual-use goods are a central topic in international security and trade, the global community has not yet agreed on a clear and universal definition of what exactly qualifies as a "dual-use" item.
Instead of using one single definition, most international regulations rely on a few key contrasts or dichotomies, such as civilian vs. military, or peaceful vs. non-peaceful uses, to describe the dual nature of these technologies. These approaches highlight the potential of a product to be used for both constructive and harmful purposes, depending on the context and intent.

Over time, new threats have prompted additional frameworks that distinguish between benevolent and malevolent uses, beyond just civil vs. military. In this light, dual-use goods are often understood through two key dimensions:

- their technical characteristics, which make them adaptable to more than one function;
- the intent or goal of the user, which defines whether the use is peaceful or hostile.

This flexible and evolving understanding reflects the growing complexity of global security and technological innovation [1].

The notion of dual use originated in the field of international security and export control, long before its application to space activities. During the Cold War, policymakers began to recognize that many scientific and industrial technologies developed for peaceful purposes could also serve military ends.
The earliest use of the term appeared in the context of nuclear and chemical regulation. Treaties such as the Nuclear Non-Proliferation Treaty (NPT), the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC) aimed to ensure that sensitive materials and know-how would be used only for peaceful purposes [2].
However, these agreements implicitly acknowledged that a complete separation between civil and military domains was impossible, since many technologies (such as nuclear reactors, biochemical equipment or advanced computing) could easily shift from legitimate scientific research to military applications depending on intent [1].

From the 1970s onward, this ambiguity became institutionalized through export-control systems such as the Wassenaar Arrangement, the Missile Technology Control Regime (MTCR) and later the European Dual-Use Regulation. These frameworks introduced the concept of goods and technologies "that can be used for both civil and military purposes", attempting to manage their diffusion through licensing and restricted transfer [2]. Yet, these definitions remained practical rather than conceptual, focusing on regulatory control instead of clarifying the nature of dual use [1].

In the 1990s, with the end of the Cold War and the acceleration of globalization, the relationship between civilian and defence sectors began to invert.
Whereas innovation had previously flowed from military research into the civilian economy, it increasingly started moving in the opposite direction, as commercial technologies, from telecommunications and navigation to information processing, were "spun in" to military applications. This reversal transformed dual use from a problem of control to one of dependence: national defence systems became reliant on civilian and commercial technologies for their functioning and modernization [3].

The growing interconnection between civil and defence industries also gave rise to new economic and political interpretations of dual use. It evolved into a structural condition of innovation in which the same research and industrial ecosystem supports both markets simultaneously. This understanding moved beyond the notion of accidental overlap and toward a deliberate integration strategy, where dual use became a tool for efficiency, cost reduction and technological leadership [4].

Finally, in the early 2000s, the concept extended explicitly to the space sector. Space infrastructures naturally serve multiple purposes: launch vehicles, remote-sensing instruments and satellite constellations developed for civilian use, such as communication or Earth observation, can be adapted to support defence and intelligence operations. This inherent duality has made outer space one of the most visible and complex domains for the application of the dual-use paradigm.
In summary, the historical development of the dual-use idea mirrors the evolution of technology itself, from state-controlled strategic assets to globally diffused commercial systems [5], [6].

2.2 Extension to the Space Domain

As anticipated, the concept of dual use finds one of its clearest expressions in the space sector. Since the beginning of the space age, technologies developed for exploration, communication and observation have simultaneously held military relevance. The same launch vehicles that place scientific satellites into orbit can deploy military payloads; the same sensors used for environmental monitoring can collect strategic intelligence data. This inherent versatility makes outer space a paradigmatic example of dual-use interdependence [5].

Initially, during the Cold War, space activities were driven almost exclusively by national governments for strategic and prestige purposes. Civilian programmes such as NASA's Apollo missions or the Soviet Soyuz system coexisted with highly classified military projects, but the boundary between them was politically reinforced. Over time, however, the increasing miniaturization of technology and the diffusion of commercial capabilities progressively blurred that division. With the emergence of New Space actors, commercial companies began providing services, such as imaging, communications and launch operations, that were once the exclusive domain of states [3].

Japan was among the first countries to adopt an explicit dual-use policy in the management of its space programme. After decades of constitutional restrictions

on military activity, Japan redefined its national space policy in the early 2000s to allow satellites and infrastructures to serve both civil and defence objectives.
This shift created an integrated model of space governance that improved efficiency, fostered industrial competitiveness and aligned the country's technological capabilities with evolving security demands.
Similar dynamics can be observed in Europe, where programmes such as COSMO-SkyMed and TerraSAR-X operate under institutional arrangements designed to satisfy the needs of both scientific users and defence agencies [5].

The growing overlap between civil and military applications has also raised new questions of responsibility and legality. In fact, international law remains fragmented in addressing the dual-use nature of space systems [6]. The Outer Space Treaty (OST) obliges states to conduct activities "in accordance with international law", but it does not clarify how to treat assets that perform both civilian and military functions. In modern conflicts, such as the war in Ukraine, commercial satellite constellations have provided critical communication and intelligence services to armed forces, making them potential military objectives [7].
This situation illustrates the risk that privately operated, civilian-labelled systems may lose their protection if they directly contribute to hostilities, thereby challenging long-standing principles of distinction and proportionality [8].

The NATO Parliamentary Assembly Report on Critical Dual-Use Technologies [3] highlights how commercial innovation now drives most technological progress in the space domain. Militaries increasingly rely on commercially developed systems, particularly satellite networks, artificial intelligence and communication infrastructures, which are subsequently adapted for operational purposes.
This reversal of innovation flow, from civilian to defense applications, exemplifies the global trend of technological interdependence identified by the Alliance. It also underscores the need for coordinated export controls and shared ethical standards to prevent the misuse of dual-use capabilities.
In this context, dual use in space should not be understood as an anomaly but as a structural characteristic of the domain itself.
Satellites inherently serve multiple communities, as the scientific, commercial and military ones, through shared or overlapping infrastructures. This convergence enhances efficiency but simultaneously complicates transparency and security.
The challenge is therefore not to eliminate dual use, which is intrinsic to space activities, but to manage it through clear legal interpretation and responsible innovation [6], [8].

In conclusion, the extension of the dual-use concept to the space domain reflects both technological reality and strategic necessity. As the boundary between public and private actors continues to blur and, as space becomes increasingly central to communication and navigation, understanding its dual-use nature is essential for shaping future policies.

2.3 Policy Insights

Building on this perspective, the policy dimension of dual use in space emerges as one of the most complex and dynamic aspects of modern governance. The coexistence of civil and military objectives within the same infrastructures requires legal and institutional mechanisms capable of balancing competitiveness and security. Current frameworks still struggle to address the implications of commercial actors operating in domains traditionally reserved for governments [2].

As the distinction between civil and defense applications continues to blur, several scholars have emphasized that regulatory clarity must evolve alongside technological progress. International law remains fragmented and uncertain when applied to dual-use space systems, particularly regarding state responsibility for privately operated satellites [6] and the accelerating “spin-in” of commercial technologies into defense capabilities demands coordinated policies among allied nations to safeguard both innovation and security [3].

From a European perspective, recent initiatives (such as COSMO-SkyMed and Galileo) illustrate a pragmatic approach in which civil and military objectives are jointly pursued under integrated management structures. Yet, the deliberate intermingling of civilian and defense assets also risks contravening humanitarian principles of separation, complicating the lawful conduct of operations in space.
These issues underscore the urgent need for a renewed policy framework that reconciles innovation with accountability and ensures that dual-use technologies contribute to global security rather than instability.
Chapter 3 will therefore examine in depth the existing legal and policy instruments governing dual-use space activities, highlighting their limitations and the emerging challenges they face.

2.4 Classification Of Dual Use Satellite Domain And Case-Based Evidence

Understanding dual use in the space sector requires analyzing the main functional domains in which civil and defense objectives coexist. These include Earth observation, navigation and communication satellites, as well as emerging technologies such as mega-constellations and AI-based systems.

Each of these domains demonstrates a specific form of technological and institutional overlap, where systems designed for peaceful or commercial use can simultaneously support military and security operations.
The following subsections illustrate these dynamics through concrete examples.

2.4.1 Dual-Use in Earth Observation Satellites

Earth observation (EO) represents one of the most evident and consolidated examples of dual-use technology.
EO satellites collect high-resolution data that serve multiple civilian purposes, such as environmental monitoring, disaster management, agriculture and urban planning. At the same time, the same data and imaging capabilities are essential for military reconnaissance, target detection and surveillance operations [9].

A clear example of this duality is the **COSMO-SkyMed** constellation, jointly developed by the Italian Space Agency (ASI) and the Ministry of Defence.
This system consists of four X-band Synthetic Aperture Radar (SAR) satellites operating in Low Earth Orbit, capable of providing imagery in all weather and illumination conditions. Through its dual-access architecture, COSMO-SkyMed serves both civilian users (via the Matera ground segment) and military users (via the Pratica di Mare control center).
Such configuration allows flexible and rapid tasking of the same satellites for different end-users, enabling Italy to optimize public investment while strengthening national and international security capacities. [9]
From an operational perspective, the constellation provides key services for land and maritime surveillance and environmental risk prevention. For instance, COSMO-SkyMed data are regularly employed for mapping flood events and landslides, monitoring agricultural productivity and detecting illegal activities at sea, while simultaneously contributing to defense reconnaissance missions.
Its interoperability with other systems, illustrates how civil–military cooperation can extend to international partnerships, reinforcing both scientific and strategic objectives.

In this sense, Earth observation stands as a paradigmatic case of the dual-use paradigm: a single technological infrastructure supporting both sustainable development and national security through shared space capabilities. [9]

2.4.2 Dual-Use in Navigation Satellite Systems

Navigation satellite systems represent another clear manifestation of the dual-use paradigm. Originally conceived for military applications, they have progressively

evolved into indispensable infrastructures for civilian life.
Global Navigation Satellite Systems (GNSS) such as the American **Global Positioning System (GPS)**, the European **Galileo**, the Russian **GLONASS** and the Chinese **BeiDou**provide positioning, navigation and timing (PNT) services that are essential for transportation, logistics, agriculture and telecommunications worldwide.
At the same time, these systems retain critical military functions such as encrypted positioning, missile guidance and synchronization of defense communications and operations [10].

From a historical perspective, **GPS** was developed by the U.S. Department of Defense during the Cold War to provide accurate geolocation for strategic and tactical missions. Its civilian signal was opened for public use in 1983, but the system continues to maintain a **secure military channel (P(Y) code)** available exclusively to authorized defense users. This structure epitomizes dual use: one global infrastructure serving both peaceful navigation and precise military targeting.

The European **Galileo** program was conceived with a similar dual logic but under civilian governance. Although managed by the European Union, Galileo includes a specific encrypted service called the **Public Regulated Service (PRS)**, designed to guarantee secure positioning for governmental and defense applications even in case of jamming or spoofing. PRS access is restricted to authorized public bodies such as police, border control, civil protection and military forces, ensuring resilience against interference while maintaining interoperability with civilian users [10].
This architecture demonstrates the European Union's attempt to balance strategic autonomy with the open-access principle of space systems. While the open signal supports economic and scientific activities, ranging from autonomous vehicles to precision farming, the PRS strengthens Europe's ability to operate independently in crisis situations, including those involving national security or defense coordination. Such dual governance, combining civilian management with defense capability, makes Galileo an emblematic case of the modern dual-use approach to space technology.

More broadly, GNSS constellations exemplify how dual use has become embedded in space infrastructure: the same signal that enables global commerce and transport also underpins critical defense operations and cyber resilience. As technological dependence on precise timing and positioning continues to grow, navigation satellites will remain central to both the civilian economy and military strategy worldwide. [10]

2.4.3 Dual-Use in Communication Satellite Networks

Communication satellites have become one of the most hybrid and controversial expressions of dual use in space.
Originally designed to provide global connectivity and bridge digital divides, modern constellations of broadband satellites are now deeply intertwined with military operations and strategic communication infrastructures [11]. The line between commercial service provision and defense application has therefore become increasingly blurred.

A clear example of this phenomenon is the use of the **Starlink** satellite network during the conflict in Ukraine.
Developed and operated by the private company SpaceX, Starlink provides low-latency broadband services through a large constellation of Low Earth Orbit (LEO) satellites.
While initially deployed for civilian communications and internet access, the system rapidly became a critical asset for maintaining Ukrainian command-and-control and intelligence links during the 2022 Russian invasion. The network enabled military units to communicate securely even in areas where terrestrial infrastructures were destroyed or jammed, effectively turning a commercial system into a dual-use strategic capability [7].

From an operational standpoint, this case illustrates how the growing dependence on commercial satellite networks extends military resilience but also introduces vulnerabilities.
Private actors, whose systems are used in wartime, may unintentionally become parties to a conflict, blurring traditional notions of neutrality and civilian protection under the Law of Armed Conflict. Commercial satellites that directly support military activities may lose their protection as civilian objects, thus becoming potential legitimate targets under international humanitarian law [7].

At the policy level, institutions such as NATO have acknowledged that commercial innovation has become a cornerstone of defense modernization. According to Baldwin [3], commercial space systems, including communication constellations like Starlink, are now essential components of allied deterrence and resilience strategies. However, this integration requires new regulatory and contractual frameworks to manage security clearances, data protection, and operational control in crisis situations.

The Starlink example highlights both the opportunities and risks inherent in dual-use communication networks. On one hand, they offer flexible, rapidly

deployable connectivity that enhances military effectiveness and civilian resilience alike. On the other, they complicate international law, challenging traditional distinctions between public and private, civilian and military actors in space.
These systems thus embody the essence of the dual-use dilemma: a technology that advances societal progress while simultaneously transforming the strategic landscape of modern warfare.

2.4.4 Military Satellites: Declared Systems and Grey Zones

While military satellites are not dual-use systems in the strict sense, they represent an essential reference point for understanding the boundaries of the dual-use spectrum.
Unlike civilian or commercial constellations that may later be repurposed for defense, dedicated military satellites are explicitly designed for strategic and intelligence functions such as secure communications, electronic reconnaissance or missile early warning. However, even within these programs, technological convergence and international cooperation increasingly blur the distinction between military and civilian infrastructures [6].

An illustrative example is the Russian *Luch-Olymp*, launched in 2014 and operated by the Ministry of Defence in cooperation with civilian industrial partners.
Officially classified as a communication relay satellite, it has been repeatedly observed maneuvering near commercial satellites belonging to Intelsat and other operators, suggesting potential signals intelligence (SIGINT) activities and data interception capabilities [12].
These orbital behaviors, monitored by independent space situational awareness networks, indicate that even declared military platforms may perform multi-domain tasks that overlap with civil or commercial space assets [11].

The case of Luch-Olymp highlights a key aspect of the *"grey zone"* between overt military space programs and dual-use systems. On the one hand, such satellites maintain explicit defense designations and operate under national command structures; on the other, their use of shared orbital regimes and communication frequencies creates interdependence with the broader space ecosystem.
This proximity raises the risk of misinterpretation, accidental interference or escalation, particularly when satellites maneuver near assets operated by other states or private companies .

In policy terms, these grey-zone activities underscore the limitations of the existing international framework, which does not require states to disclose the exact capabilities or purposes of their satellites. The absence of transparency and verification mechanisms facilitates a form of strategic ambiguity that undermines confidence-building in space [13].

Ultimately, declared military satellites serve as a benchmark to define the outer boundary of dual use. They reveal how modern military programs rely on technologies, orbits and partnerships that are often shared with civilian sectors, confirming that in the contemporary space domain, absolute separation between military and civilian infrastructures has become largely theoretical. This aspect will be explored in more detail in *Chapter 4*, where the methodological framework of the research is presented.

2.4.5 Emerging Technologies and the Evolution of Dual-Use Capabilities

Emerging technologies are rapidly transforming the scope of dual-use space applications. Artificial intelligence, quantum communications and responsive launch systems are increasingly developed in the commercial sector but carry clear strategic implications for defense and security. AI-driven data analysis enhances satellite autonomy and intelligence processing, while quantum networks promise ultra-secure communication channels with potential military advantages.

The diffusion of innovation between civilian and defense research accelerates technological progress but simultaneously makes control and regulation more complex [4]. These trends confirm that dual use is no longer limited to traditional space hardware but extends to the digital and algorithmic infrastructures that sustain the future of space operations.

Chapter 3

Legal Framework And Its Limitations

This chapter explores the main legal and policy instruments currently in force, ranging from export control regimes to space treaties and humanitarian law and highlights their limitations in managing the dual-use nature of satellite systems. The objective is not only to identify gaps but also to question the adequacy of existing definitions and enforcement mechanisms when civilian and military applications are increasingly blurred.

By analyzing both binding treaties and soft-law approaches, and reviewing case-specific interpretations, this chapter gives the foundation for why a new classification model is necessary in Chapter 4.

3.1 Outer Space Treaty - OST

The **Outer Space Treaty (OST)**, signed in 1967, serves as the foundational legal framework governing the activities of states in outer space.
It establishes key principles such as the freedom of exploration *(Article I)*, the prohibition of national appropriation *(Article II)*, and the non-deployment of nuclear weapons or weapons of mass destruction in orbit or on celestial bodies *(Article IV)*.

The OST has been widely ratified and remains the cornerstone of international space law, aiming to preserve space for peaceful purposes and cooperative use. However, despite its significance, the OST contains several ambiguities that make it ill-suited to address the realities of dual-use space technologies.
While Article IV explicitly bans the placement of weapons of mass destruction in space, it does not prohibit the use of space-based systems for military support

operations, such as surveillance, reconnaissance or communication. This omission has allowed for the rapid proliferation of military and dual-use satellites under the broad label of "peaceful use".

The term *"peaceful purposes"* itself is not clearly defined within the treaty. In practice, it has been interpreted to mean "non-aggressive" rather than strictly "non-military". This distinction has enabled states to justify the deployment of dual-use satellites and even military space assets, as long as they are not explicitly offensive or weaponized. As a result, the OST lacks the legal clarity needed to effectively regulate technologies that straddle the line between civilian and strategic applications.

Furthermore, the treaty offers no mechanism to monitor compliance with its provisions or to verify the nature and function of satellites launched into orbit. In an era where commercial and governmental actors increasingly share infrastructure, launch services and data, this absence of verification tools aggravate concerns over transparency and accountability in space.

In short, while the Outer Space Treaty set a valuable precedent for international cooperation and the demilitarization of celestial bodies, it is no longer sufficient to govern the complexities of modern dual-use space technologies. Its vague terminology, permissive interpretation of military support functions, and lack of enforcement mechanisms leave significant gaps in the regulation of contemporary space activities[14], [15].

3.2 Export Control Regimes

Export control regimes represent one of the first lines of regulation for dual-use technologies. These mechanisms were designed to restrict the spread of technologies that could contribute to weapons proliferation.
The three most relevant frameworks for space-related dual-use issues are:

3.2.1 MTCR - Missile Technology Control Regime

The **Missile Technology Control Regime (MTCR)** is a voluntary export control arrangement established in 1987 with the primary goal of limiting the proliferation of delivery systems for weapons of mass destruction (WMD), specifically those other than manned aircraft. The MTCR focuses on controlling the transfer of technology, equipment and software that could contribute to the development of missiles capable of delivering nuclear, chemical or biological weapons [16].

The regime's key documents include:

- The MTCR Guidelines, which define the objectives and guiding principles for member states
- the Equipment, Software and Technology Annex, which details specific items subject to control. It is divided in two main categories:
    - **Category I items**: These include complete rocket systems such as ballistic missiles, space launch vehicles (SLVs) and cruise missiles with a range of at least 300 km and a payload of at least 500 kg. It also covers critical subsystems such as rocket engines, guidance systems, and production facilities.
    - **Category II items**: These include a wider range of dual-use components and technologies that could be used in less capable missile systems or in systems with a primary civilian use but a potential military application.

While the MTCR explicitly states that it is not designed to hinder national or international space programs as long as they are not intended for WMD delivery, the overlap between SLV and missile technologies has led to restrictive interpretations, particularly by the United States.
Historically, the United States has applied the MTCR guidelines with extreme caution, adopting a policy that effectively treated most SLV transfers as presumptively dangerous, even to close allies.
This strict interpretation had the unintended consequence of:

- Limiting cooperation with friendly states in civilian space programs;
- Reducing the competitiveness of the U.S. commercial space sector;
- Driving allies toward alternative suppliers, including Russia and China.

However, in January 2025, the U.S. announced a significant policy shift:

- It now supports case-by-case evaluation of MTCR Category I systems, including SLVs and certain unmanned aerial systems (UAS), especially for trusted partners with robust export control frameworks.
- The new approach is designed to align better with the current strategic environment, strengthen the U.S. defense industrial base and expand space partnerships with allies [17].

While the MTCR plays a significant role in keep back the proliferation of missile technologies, it faces important challenges that limit its effectiveness in today's dynamic and commercialized space environment. One of the main issues lies in the technological overlap between space launch vehicles (SLVs) and ballistic missiles. These systems share nearly identical technical components, such as propulsion, guidance and staging mechanisms, which makes it extremely difficult to regulate one without inadvertently imposing restrictions on the other. As a result, attempts to prevent the spread of missile technology often come at the cost of hindering legitimate space exploration and cooperation.

Another problem is the regime's lack of flexibility. In fact its rigid categorization of systems into Category I and II does not adequately reflect contemporary innovations such as micro-launchers, reusable vehicles or hybrid platforms that combine civilian and military functions. These technologies fall into *grey zones* that the MTCR was never designed to manage.

Additionally, the regime suffers from divergent national interpretations. That is because while some countries adopt a pragmatic approach, the United States has historically enforced the guidelines more stringently than other MTCR partners, often treating even commercial space technologies as potential proliferation risks. This has created strategic imbalances and occasionally pushed allied nations to go for alternative technology sources from non-aligned countries, like Russia or China, undermining the very purpose of the regime.

This last complication arises by the fact that there is a limited membership of the MTCR. As stated before, in fact, crucial space powers such as China are not members and this creates regulatory loopholes that adversaries can exploit. The absence of global consensus and enforcement mechanisms weakens the regime's ability to contain sensitive technology flows in an increasingly interconnected commercial market.

In the specific context of dual-use space technologies, these limitations become even more pronounced. The MTCR does not explicitly regulate satellite payloads, data transmission, or commercial satellite services, even though these can play critical roles in modern military operations, ranging from reconnaissance to precision targeting. This creates a regulatory blind spot, where capabilities with clear strategic value are left outside the scope of traditional non-proliferation frameworks. At the same time, new private actors, especially those working on AI-enabled sensors, high-resolution imaging, and radiofrequency intelligence, operate across borders and often beyond the reach of national export controls. As a result, the current regime struggles to keep pace with the dual-use reality of today's space ecosystem.

3.2.2 ITAR - International Traffic in Arms Regulations

The **International Traffic in Arms Regulations (ITAR)** is a U.S. legal framework designed to control the export of defense-related articles and services listed in the United States Munitions List (USML). Although primarily created to safeguard national security and prevent the proliferation of military technologies, ITAR has had significant and sometimes unintended consequences in the context of space systems.

One of the key limitations of ITAR in the space domain lies in its difficulty distinguishing between civilian and military uses. Many satellite components, software and even data handling systems are regulated under ITAR not because of how they are used, but because of their inherent technical capabilities. For example, a satellite equipped with high-resolution imaging technology may serve a wide range of civilian functions, from environmental monitoring to disaster management, yet be classified as a defense article due to its potential military applicability. This blurred boundary between civilian and military space applications reflects a structural ambiguity in the ITAR regime.

This rigidity creates challenges for international cooperation, innovation and commercial competitiveness. ITAR does not adequately account for how space systems are actually used, focusing instead on design specifications and technical thresholds. As a result, commercial satellites or services developed for peaceful purposes may still fall under restrictive export controls simply because they possess features deemed sensitive. At the same time, the regulation offers little clarity on more modern dual-use risks, such as AI-driven onboard processing, advanced radio frequency (RF) sensing or the delivery of satellite-based data services, all of which fall outside ITAR's traditional scope but carry clear strategic value.

In essence, ITAR's framework is built around Cold War-era distinctions that struggle to reflect the complexity of today's space ecosystem. Its approach, primarily hardware-focused and centered on presumed intent, does not align with the evolving realities of dual-use capabilities, where the line between civilian benefit and military potential is increasingly difficult to draw.
This results in both overregulation of benign technologies and under regulation of emerging threats, underscoring the need for more adaptive and function-oriented governance mechanisms [18], [19], [3].

3.2.3 Wassenaar Arrangement

The **Wassenaar Arrangement** is a voluntary multilateral export control regime that seeks to promote transparency and responsibility in the trade of conventional arms and dual-use goods and technologies. It includes 42 participating states and maintains detailed control lists covering sensitive items, including space-related components such as launch vehicles, sensors and encryption technologies.

However, the Wassenaar Arrangement faces significant limitations when it comes to regulating dual-use space technologies. First, its reliance on predefined technical categories means it often fails to capture emerging capabilities, such as AI-enabled satellites or integrated constellations, that fall outside static definitions. Second, the regime does not include major space powers like China, creating loopholes in global control efforts.

Moreover, Wassenaar regulates what is exported, but not how technologies are ultimately used. This is particularly problematic in space, where the same system can serve both civilian and military ends. There is no mechanism within the arrangement to monitor or prevent the shift from peaceful to strategic applications after export approval.

In summary, while Wassenaar provides a baseline for export control coordination, its limited scope and slow responsiveness reduce its effectiveness in managing the real-world challenges posed by dual-use space systems [20].

3.3 International Humanitarian Law (IHL)

International Humanitarian Law (IHL), also known as the law of armed conflict, provides a legal framework for the conduct of hostilities. Its core principles include the protection of civilians and civilian objects, the obligation to distinguish between military and civilian targets and the requirement that any military action be proportionate and necessary.

However, the increasing reliance on commercial space infrastructure for military purposes has introduced new legal challenges.

When a satellite originally intended for civilian use (as Earth observation, communication or navigation) is repurposed to support military operations, it may lose its protection under IHL and become a lawful target. This blurs the traditional lines between civilian and military objects in conflict, complicating compliance with the principle of distinction.

Moreover, the principle of proportionality prohibits attacks that would cause excessive harm to civilians in relation to the anticipated military advantage. Striking a dual-use satellite used for both civilian internet services and military command support, for instance, raises difficult legal and ethical questions.

Another complicating factor is the lack of transparency in satellite operations.

Many systems are owned by private entities or operated under public-private partnerships and their dual-use functions are not always publicly declared. This creates a risk of misinterpretation and accidental escalation during conflicts, especially when hostile actors cannot reliably distinguish civilian from military space assets. In summary, IHL was developed with terrestrial warfare in mind, and its application to space remains underexplored and inadequately codified. As commercial satellites increasingly serve military functions, the need to clarify how the laws of war apply in outer space becomes urgent [21] [22].

3.4 Private Actor Responsability

As commercial actors increasingly take on critical roles in space infrastructure, questions of legal responsibility and accountability have come to the forefront of international space governance. Companies such as SpaceX, Planet Lbas and Maxar Technologies are now key providers of satellite data and broadband communication capabilities, some of which are directly supporting military operations on the ground. This shift challenges traditional legal frameworks, which were primarily designed to regulate the conduct of states and not private entities.

International space law, including the Outer Space Treaty (OST), does not provide explicit provisions regarding the legal responsibilities of private actors in armed conflict. Article VI of the OST holds states internationally responsible for national space activities, whether conducted by governmental or non-governmental entities. However, the treaty remains vague on how that responsibility is shared or delegated when a private company's infrastructure is used for military purposes. This creates legal ambiguity in scenarios where a commercial satellite constellation, owned and operated by a private entity, becomes involved in the conflict.

Recent cases, such as the use of Starlink to support Ukrainian defense communications, have sparked debate over whether private companies should be considered lawful participants in hostilities or mere service providers. Additionally, organizations like UNOOSA have highlighted the growing complexity of public-private partnerships (PPPs) in space operations. These partnerships blur the line between state and non-state activities, making it increasingly difficult to determine who is responsible for ensuring compliance with international law.

Chapter 4

Research Design

This thesis investigates how satellite systems with dual-use potential can be classified more effectively using a spectrum-based approach.
Traditional frameworks tend to adopt a binary distinction between "civilian" and "military" space assets, which doesn't take into consideration the operational ambiguity and technological complexity of modern space infrastructure.
In fact with the rise of commercial actors, advanced sensor technologies and integrated defense applications, the line between civil and military usage has become increasingly blurred.

The central research question guiding this study is: "How can we better estimate the degree of dual-use features in contemporary satellite systems and what technical and operational indicators can support this classification?"
To address this question, the study proposes a multi-criteria, semi-quantitative methodology that evaluates satellites based on a range of **physical, functional and organizational features.** The goal is to move past legal definitions and develop a measurable and flexible model that reflects how satellites are operated and potentially employed.
Ultimately, the objective is to provide a tool that supports the evaluation of space systems not only by their declared mission, but also by their inherent capabilities and potential for strategic repurposing. In doing so, the model offers a scalable framework that can adjust to changing technologies and global dynamics.

To do so, the research adopts an empirical and inductive methodology, in which general insights about dual-use characteristics are derived from the systematic analysis of existing satellite missions and the process involves the following sequential steps:

1. Identification of reference military satellites as a benchmark to define the

typical features of defense-oriented systems.

2. Collection and harmonization of satellite data from multiple open and institutional sources.

3. Definition of the parameters capable of capturing the degree of potential military or strategic use.

4. Development of a scoring and weighting method to convert these qualitative traits into a quantitative index.

5. Identification and discussion of methodological limitations to ensure contextual understanding of the results.

Through this process, the research builds a structured foundation for the following chapters: *Chapter 5* will describe the parameters and subcategories with their scores, while *Chapter 6* will present the construction of the Index itself. *Chapter 7*, eventually, will analyze the trends of the results.

4.1 Definition of a Military Satellite

To better comprehend the degree of ambiguity for each satellite, it is necessary to examine in detail the technical and operational features that characterize military space systems. Military satellites are not defined merely by their declared mission, but by a combination of payload capabilities, communication architectures, security requirements and operational procedures that collectively enable defense-oriented functions.

Understanding these characteristics is an essential preliminary step, as they form the empirical benchmark from which dual-use indicators are later derived. Through this analysis, it becomes possible to distinguish not only what military satellites do, but also how they are designed and operated, elements that often reveal defense relevance even in systems nominally classified as civilian.

Military satellites come in various types, each designed for specific missions and embedded within broader strategic objectives. In general, their core functions can be grouped into a limited number of mission categories that reflect long-standing defense needs.

For each category, specific technical features are consistently employed to guarantee reliability, security and operational effectiveness. These recurring patterns form the empirical basis for the parameters identified later in the research design.

4.1.1 Military Navigation Satellites

Military navigation satellites provide Positioning, Navigation and Timing (PNT) services that are essential for modern armed forces. These systems allow military units to coordinate movements across all domains, navigate safely in degraded or unfamiliar environments and synchronize operations that rely on precise timing.
In contemporary warfare, timing accuracy is as critical as positional accuracy: encrypted time signals enable secure communications, missile guidance, air–ground coordination. As highlighted in military analyses, PNT availability has become fundamental to maintaining information superiority and operational tempo.

Compared to civil navigation services, the military segment is engineered to ensure robustness, continuity and protection from intentional interference. Military forces depend on these satellites for both strategic functions and tactical applications like target designation and battlefield mobility [23].

Some key required characteristics include:

- **Encrypted military signals** , such as GPS M-Code or Galileo PRS, which prevent spoofing and restrict access to authorized defense users.
- **Anti-jamming and anti-spoofing techniques**, allowing continued operation under deliberate electromagnetic interference.
- **Radiation-hardened atomic clocks**, ensuring precise and stable timing even under adverse environmental conditions.
- **High-power L-band transmissions** providing global availability and improved robustness compared to civilian signals.

Representative examples are described in Table 4.1.

4.1.2 Early Warning Satellites

Early-warning satellites are dedicated systems designed to detect ballistic missile launches and other high-energy events by observing infrared emissions from space. Their primary contribution is to provide rapid and continuous missile-launch detection, enabling national authorities to assess threats, activate defensive measures and preserve strategic stability.
Because missile launches produce intense heat signatures during the boost phase, early-warning satellites represent the first layer of detection in a missile defense architecture, complementing ground-based radars and airborne sensors. They also contribute to broader situational awareness by monitoring nuclear tests, large

System	Country	Orbit	Description
GPS	USA	MEO(∼20,200 km)	Provides encrypted M-Code for U.S. and NATO forces offering high anti-jam resilience and global coverage.
GLONASS	Russia	MEO(∼19,100 km)	Uses restricted-access military codes for secure national navigation and reliable performance at high latitudes.
Galileo PRS	EU	MEO(∼23,200 km)	Encrypted Public Regulated Service for governmental and defence use, with high clock stability.
BeiDou	China	MEO-GEO-IGSO	Offers restricted military navigation services using a hybrid architecture optimised for Asia-Pacific regional coverage.

Table 4.1: Representative Military Navigation Systems

explosions, re-entry events and other high-temperature phenomena.
Their design is tightly integrated with national command-and-control systems, often linking directly to missile defense networks and strategic communication nodes.

Key characteristics required by military early-warning systems include:

- **High-sensitivity infrared telescopes**, capable of detecting missile plumes during the boost
- **Orbital configurations in GEO and HEO**, ensuring persistent visibility of launch corridors and long dwell time over northern latitudes.
- **Secure and high-speed data relay links**, enabling near-real-time transmission of alerts to strategic command authorities.
- **Onboard processing**, reducing false alarms and improving the reliability of launch detection.

Some representative examples in Table 4.2

Name	Country	Orbit	Description
DSP	USA	GEO	The Defense Support Program provides continuous infrared surveillance for missile-launch detection and has long served as a foundational component of U.S. strategic warning systems [23].
SBIRS	USA	GEO/HEO	The Space-Based Infrared System combines geostationary satellites and highly elliptical payloads, offering enhanced sensitivity, faster reporting and improved detection of modern missile threats [23].
Tundra/ EKS	Russia	HEO/Molniya	Next-generation Russian early-warning satellites designed for persistent coverage of northern latitudes, featuring advanced infrared payloads and secure communication links [24].

Table 4.2: Representative Early-Warning Satellite Systems

4.1.3 Reconnaissance and Imaging Satellites

Reconnaissance and imaging satellites provide optical, infrared and radar-based observations that are fundamental to military intelligence, targeting and operational planning. They enable the detection and monitoring of strategic sites, troop movements, infrastructure, maritime activity and changes in adversary activities. These systems support a wide range of missions and are among the most versatile and widely used assets in defense space architectures.
Military reconnaissance satellites must ensure both high-resolution detail and persistent coverage, often operating under conditions where cloud cover, night-time or camouflage could otherwise limit visibility. For this reason, modern constellations combine different sensing modalities (optical, multispectral, infrared and Synthetic Aperture Radar) to ensure reliable intelligence collection in all environmental conditions.

Key characteristics required by military reconnaissance systems include:

- **High-resolution electro-optical telescopes**, delivering detailed imagery for identification of targets, installations and activities on the ground.

- **Multispectral and hyperspectral sensors**, enabling material discrimination, camouflage detection and environmental analysis.
- **Infrared detectors**, supporting night-time and thermal imaging tasks.
- **Synthetic Aperture Radar (SAR) instruments**, providing all-weather and day/night observation independent of cloud cover or illumination.
- **High-capacity secure downlinks**, ensuring that large amounts of imagery and sensor data reach intelligence centers without delay.

Representative military systems are described in Table 4.3

Name	Country	Orbit	Description
Keyhole/ CRYSTAL	USA	LEO	High-resolution electro-optical reconnaissance satellites considered the technological backbone of U.S. strategic imagery collection.
SAR-Lupe	Germany	LEO	A fully military SAR constellation providing high-resolution radar imagery for both tactical and strategic intelligence missions [23].
COSMO-SkyMed	Italy	LEO	A SAR system delivering defence-grade high-resolution imagery with rapid revisit capabilities and secure high-rate downlinks.

Table 4.3: Representative Reconnaissance and Imaging Satellite Systems

4.1.4 Signals Intelligence (SIGINT) Satellites

Signals Intelligence (SIGINT) satellites collect, intercept and analyse electromagnetic emissions across a wide range of frequencies to support military intelligence, electronic warfare and strategic situational awareness. Unlike reconnaissance satellites, which observe physical features through optical or radar sensors, SIGINT spacecraft operate as advanced listening platforms: they detect radar pulses, telecommunications signals, telemetry streams and other electronic signatures emitted by adversary systems.

These capabilities allow armed forces to understand the disposition of enemy air-defense networks, map radar coverage, monitor military communications, track missile tests and detect changes in electronic activity that may indicate mobilization. They are able to provide insights that cannot be obtained through imagery alone. Because their mission requires the detection of faint or highly directional signals, SIGINT satellites are engineered with extremely sensitive receivers and large deployable antennas, often positioned in strategic orbital slots to ensure persistent geographic coverage.

Key characteristics required by military SIGINT systems include:

- **Large-aperture and high-gain antennas**, needed to intercept weak or distant electromagnetic emissions. GEO SIGINT spacecraft may use antennas exceeding 20 meters in diameter.
- **Broadband RF receivers** capable of monitoring multiple frequency bands simultaneously, from HF communications to microwave radar signals.
- **Geolocation instruments**, allowing the precise identification of emitter positions using triangulation or time-difference-of-arrival techniques.
- **Secure and encrypted downlinks**, ensuring intercepted material reaches intelligence centers without risk of compromise.

Representative military systems are described in Table 4.4.

4.1.5 Military Communication Satellite - MILSATCOM

Military communications satellites (MILSATCOM) provide the secure, resilient and globally distributed communication links that enable modern defense operations. They support strategic command and control, theatre-level coordination and tactical connectivity for deployed forces operating far from national infrastructure. Military variants are engineered to ensure survivability, protection and guaranteed access in contested or degraded environments.

Key characteristics required by MILSATCOM systems include:

- **Multi-band communication** payloads, typically integrating **UHF** links used by mobile and maritime units, **X/Ka-band** channels supporting large data transfers and **EHF-band** capable of resisting nuclear and electromagnetic disturbances.
- **Anti-jam** and **anti-interference techniques**, such as frequency hopping, spread-spectrum modulation and advanced Protected Tactical Waveforms (PTW), enabling communication continuity under deliberate electromagnetic attack.

Name	**Country**	**Orbit**	**Description**
Orion/ Mentor	USA	GEO	A class of acknowledged GEO SIGINT satellites equipped with very large deployable antennas for global interception of radar and communications signals [25].
Trumpet	USA	HEO/ Molniya	U.S. SIGINT satellites operating in highly elliptical and low Earth orbits for regional radar monitoring and electronic order-of-battle mapping.
Tselina	Russia	LEO	Russian ELINT satellites designed for interception and geolocation of radar emissions and military communication networks [23].
Yaogan (ELINT variants)	China	LEO (triplet formations)	Part of a broad Chinese satellite series; the ELINT triplets operate in coordinated LEO formations for maritime and regional electronic surveillance.

Table 4.4: Representative SIGINT Satellite Systems

- **Inter-satellite crosslinks** (RF or optical), increasing network resilience and allowing message routing even when ground stations are degraded or inaccessible.
- **Cyber-secure architectures**, including resistance to electromagnetic pulse (EMP), radiation shielding and secure TT&C channels.

  Representative MILSATCOM are described in Table 4.5

4.1.6 Military Weather Satellites

Military weather satellites provide the environmental and atmospheric information essential for mission planning and operational decision-making. Weather conditions influence aircraft routing, ISR collection, naval operations and ground mobility, making timely and accurate meteorological data a critical enabler of operational effectiveness and risk reduction.

Name	**Country**	**Orbit**	**Description**
AEHF	USA	GEO	Provides survivable, jam-resistant EHF communications for strategic and tactical users, including nuclear command and control.
WGS	USA	GEO	Wideband X/Ka-band SATCOM constellation offering high-throughput, flexible coverage and steerable beams for U.S. and allied forces.
Syracuse IV	France	GEO	Protected X/Ka-band military communications system with secure, resilient payloads and hardened ground segment features.
Skynet 5/6	United Kingdom	GEO	UK defence SATCOM programme delivering secure X-/UHF-band connectivity with hardened payloads and high resilience measures.

Table 4.5: Representative Military SATCOM Systems

Unlike purely civilian systems, military meteorological satellites deliver rapid, theatre-specific and secure information.

Key characteristics required by military meteorological systems include:

- **Infrared (IR) and microwave radiometers**, enabling cloud profiling, precipitation tracking, temperature mapping and atmospheric moisture assessment even in adverse conditions.
- **Visible-spectrum imagers**, providing high-resolution cloud cover and surface observations essential for air operations and ISR planning.
- **Direct broadcast capabilities**, allowing deployed units to receive meteorological data on portable terminals without relying on vulnerable ground infrastructure.
- **Environmental and space-weather sensors**, detecting solar activity, radiation levels and ionospheric disturbances that may affect communications or satellite operations.

- **Secure and resilient data links**, ensuring that weather products remain accessible during crises or in contested environments.

Representative examples are described in Table 4.6.

Name	Country	Orbit	Description
DMSP	USA	LEO	Defense Meteorological Satellite Program providing visible, infrared and microwave atmospheric observations for mission planning, strategic forecasting and environmental monitoring [23].
Meteor-M	Russia	LEO	Dual-use meteorological system delivering cloud imagery, radiation monitoring and oceanographic data; operationally employed by Russian defence and emergency services.
Fengyun	China	LEO/GEO	China's national meteorological constellation operating IR/MW radiometers and storm-tracking sensors, also supporting PLA operational environmental awareness [26].

Table 4.6: Representative Military and Dual-Use Meteorological Satellite Systems

4.2 Methodological Framework

The methodological framework establishes the logical structure through which the dual-use characteristics of each satellite are evaluated. This section outlines how these dimensions were selected, how they were converted into quantitative variables and how they are ultimately combined into the scoring model that forms the foundation of the Dual-Use Index.

4.2.1 Dimensions Identification

To measure the position of each satellite along the spectrum, a set of key analytical dimensions was identified.

To ensure a coherent and balanced analysis, the selected parameters cover different domains of satellite characteristics, ranging from strictly technical attributes to aspects related to ownership, control and funding.
Having this diversification allows each dimension to captures a specific feature that can influence the satellite's degree of potential strategic or military use in distinct ways. By combining these heterogeneous characteristics, the model provides a more comprehensive and accurate representation of each satellite's dual-use potential.

The selected dimensions include:

- **Operator**: refers to the entity that owns, manages and exercises operational control over the satellite and its data. This allows to understand how the system is used, who can access its services and under what conditions data are distributed.
  This dimension reflects the degree of institutional oversight of the mission which is a strong indicator of the satellite's potential strategic role.
  In fact, satellites managed by governmental entities tend to exhibit a higher potential for defense-related use, whereas those controlled by purely commercial operators generally show lower strategic involvement.
  Therefore, this dimension serves as a proxy for understanding who ultimately controls and can influence the system's use in situations of security or crisis.

- **Primary User**: considers the main end user or beneficiary of the satellite's data and services.
  While the *Operator* dimension focuses on who owns and manages the system, Primary User examines who actually makes operational use its outputs. This distinction is essential because the same satellite may be controlled by a commercial operator but serve institutional or defense clients through dedicated data-sharing agreements or service contracts.
  Understanding the nature of the primary user therefore provides a complementary perspective on dual-use potential assessing whether the satellite's capability are integrated into civil, commercial or military activities.

- **Purpose**: identifies the main operational objective of each satellite, classifying it according to its declared mission type. In fact this dimension is divided into the main functional categories, such as Earth/Space Observation, Communication, Navigation and Technology.
  By determining the satellite's primary purpose, it becomes possible to understand how its capabilities can be exploited in practice and to what extent its mission is able to support strategic or security-related functions.

- **Detailed Purpose**: examines the specific technologies, sensors and functional configurations that define how each satellite fulfills its mission, being an

expansion of the previous cited *Purpose* category.
While the *Purpose* dimension classifies satellites by their broad operational domain, this one provides a finer level of analysis focused on the technological means and applications that determine the satellite's actual capability and intrinsic potential.

- **Orbit Class**: refers to the altitude and spatial domain in which the satellite operate, that are typically categorized as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO) and Highly Elliptical Orbit (HEO).
  Analyzing the orbit class can help to deduce the strategic value and planned coverage of a mission, along with their strategic implications.

- **Orbit Type**: considers the specific configuration and dynamics of the satellite's trajectory, such as polar or Sun-synchronous, equatorial and it is complementary to the *Orbit Class* dimension.
  These parameters reveal how the satellite's motion and geometry are optimized to serve particular operational needs and how its configuration can be exploited in both civil and defense contexts.

4.2.2 Translation of Qualitative Traits into Quantitative Scores

In order to make the model operational, the qualitative dimensions described above are translated into quantitative indicators. Each dimension is associated with a set of specific subcategories that represent the most emblematic distinctions with the goal of assessing a satellite's potential strategic use. These subcategories are defined to capture how different configurations, technologies or institutional settings influence the likelihood that a satellite might serve defense or dual-use purposes.

For each subcategory, the analysis identifies its distinctive features and typical applications, examining in which contexts such configurations are commonly employed. Based on this evaluation, a numerical score is assigned to express the degree of strategic or military potential associated with that specific configuration. Whenever a satellites belongs to more subcategory, a arithmetic average of the scores is performed.

Scores are defined on a continuous scale from 0 to 1, where:

- **0** corresponds to a **purely civil** use,
- **1** represents a **purely military** system,

- **0.5** indicates a balanced **dual-use** application.

Consequently, values below 0.5 denote predominantly civil systems that however possess some degree of dual-use potential, while values above 0.5 correspond to configurations mainly oriented toward defense or security functions but still suitable for civil applications.
This scoring method makes it possible to compare satellites in a consistent way, by turning qualitative differences into numerical values.
The resulting framework then serves as the basis for the Dual-Use Index, which combines all the individual scores to show each satellite's position on the civil–military spectrum.

Beyond the scoring process itself, it is important to highlight the distinction between the descriptive information contained in the dataset and the parameters that were modeled for the construction of the Dual-Use Index. The database integrates two different categories of data: on the one hand, there are the descriptive fields directly drawn from official sources, such as the satellite's name, launch date, country of operator which correspond to objective information that does not depend on interpretation or methodological choices.
On the other hand, the model introduces a second group of variables that are generated analytically through the scoring system. These include the dimensions previously listed with their corresponding score.
This separation between descriptive inputs and modeled outputs is clearly illustrated in the satellite summary tables presented in Section 6.2, where the top section reports factual information, while the lower section displays the scores derived from the analytical evaluation.
Maintaining this distinction is essential, as it ensures transparency in the interpretation of the Dual-Use Index and clarifies which variables originate from publicly available data and which are the result of the methodological framework developed in this thesis.

4.2.3 Design Of The Scoring Model

Once each qualitative attribute has been converted into a numerical score, these values are combined to obtain a single interpretable measure of dual-use potential. The scoring model specifies how each dimension contributes to the overall assessment and how particular cases are adjusted to reflect defense-related connections.

The model follows a weighted additive approach, where each dimension (*Operator*, *User*, *Purpose*, *Detailed Purpose*, *Orbit Class* and *Orbit Type*) contributes to the total score according to its relative importance. Dimensions that are more closely linked to institutional control and technical capability, such as *Operator* and *Detailed Purpose*, are considered to have a greater influence on the final result, while others, such as *Purpose* or *Orbit*, add contextual details that help make the classification more accurate.

The weighting approach keeps the evaluation consistent across all satellites but also takes into consideration that each factor has a different level of influence. The weights are then expressed as normalized values whose sum equals one, so that the final score represents a proportional combination of all the contributing dimensions.

In addition to the main dimensions, the model integrates a **Defense-linked** correction factor, which is a complementary element to the *Operator* category, necessary to capture those cases where a satellite, although nominally operated by a commercial or civil entity, maintains direct or indirect connections with defense institutions.
These links could include procurement agreements, public funding for development or priority data access with national defense agencies.
In practice, the aim of this dimension is to help distinguish purely private commercial operators from those that have the capacity to interact directly with governmental or military actors and not underestimate their dual-use potential. In fact such relationships often imply that the operator's assets can be mobilized or prioritized for security or defense purposes, especially in crisis or emergency scenarios.
This aspect will increase the satellite's effective strategic potential without altering its formal classification.

4.3 Data Collection

To carry out the analysis, a dedicated Excel dataset was manually compiled to study satellites launched between 2000 and 2024.
The process was conducted chronologically, ensuring that each mission was evaluated within its technological and institutional context. The primary sources used for this compilation were the **Union of Concerned Scientists (UCS) Satellite Database (2023)** [27] and the amateur web page **Gunter's Space Page** [28], which together provide comprehensive and regularly updated information on active and historical missions, including launch details, orbital parameters, operator information and stated purpose and payloads.

In order to populate all relevant fields required for the dual-use assessment framework, each satellite's attribute was examined.
Whenever available, existing information from Gunter's Space Page was verified and integrated with data obtained from official websites of national space agencies,

private commercial operators, official mission pages or document and specialized platforms such as EO Portal [29], N2YO.com [30].
This cross-referencing approach has been necessary in order to ensured consistency and to have several validations.

For large constellations and multi-satellite systems, each constellation was generally treated as a single analytical entity (with identical features and consequently identical scores) or grouped by generations, unless specific satellites presented unique features that clearly distinguished them from the rest.
Satellites with insufficient or unverifiable data were excluded from the analysis or, when only a specific field was missing, the entry was completed with the label "*Unknown*".[1]

Through this process, the dataset was fully populated and prepared for analysis. Based on this data, the scoring model was applied to assign values to each satellite, leading to the construction of the Dual-Use Index and the quantitative results presented in the following chapters.

4.4 Limits And Assumptions

While this study offers a novel and structured approach to classifying dual-use satellite systems, several limitations and underlying assumptions must be acknowledged.

First, the analysis is constrained by the availability and transparency of data. Many satellites, particularly those operated by military agencies or in authoritarian regimes, lack openly accessible technical specifications. In several cases, information about sensor capabilities, encryption standards or payload missions is not disclosed. This restricts the accuracy of scoring and may lead to underestimation or overestimation of dual-use potential.

Second, the classification process is complicated by the absence of a universal ground truth for dual-use systems. There is no internationally recognized database or benchmark that definitively labels satellites as civilian, military or dual-use. As a result, the model relies on open-source inference and contextual interpretation, both of which are sensitive to gaps or inconsistencies in reporting.

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[1] Entries marked as "Unknown" are assigned a score of 0.5, reflecting a neutral and non-biased value.

Third, the methodology is semi-quantitative and inherently subject to a degree of human judgment. Although a scoring rubric was designed to standardize assessments, certain variables, such as orbit selection or funding source, can be interpreted differently depending on geopolitical context or institutional practices. This introduces an element of subjectivity that, while manageable, should be taken into account when interpreting the index scores.

Fourth, due to the limited availability of consistent technical data, mass-related parameters could not be included in the analysis. Specifically, the total on-orbit mass (dry mass) and the in orbit fuel mass, derived from the difference between launch and dry mass, were often unavailable or incomplete in open databases.
These variables would have provided valuable insight into the maneuverability and operational flexibility of satellites, both of which represent strategically relevant factors in assessing dual-use potential.
The exclusion of these metrics therefore constitutes an additional limitation, as the capacity for orbital maneuvers can be a strong indicator of military capability.

Despite these limitations, the model provides a valuable first step in quantifying the gray zone between civilian and military space systems.

Chapter 5

Dimensions Description and Score Criteria

In this section, for every dimension, a general overview is first presented, explaining its conceptual role within the model, the rationale behind its inclusion and the reasons for the chosen subdivision into specific subcategories.
Successively all the subcategories identified within the dimension are listed and described.
The analysis outlines for each subcategory what types of satellites or missions it does include and will discuss its strategic or defense-related potential, focusing on how its characteristics can influence the overall dual-use score.
The full set of subcategories will then be presented in a summary table along with their corresponding assigned scores.
Finally, some practical examples of representative satellites belonging to every subcategory will be shown. They will include some of the most relevant satellites or constellations, helping to illustrate how the scoring logic applies to real-world systems and to validate the practical relevance of the classification framework.

5.1 Operator

The **Operator** dimension identifies the entity that owns, controls or manages the satellite system and that, accordingly with it, has the authority to influence how it is used, especially in situations which involve security or crisis response.
This dimension is highly relevant within the Dual-Use Index, as the institutional nature of the operator often determines whether a satellite can be exploited for strategic purposes. In fact, even when the satellite's declared mission is civil or commercial, the governance structure behind it can allow rapid repurposing, data sharing with defense institutions or privileged access.

For this reason, understanding who controls the system provides critical insight into its potential strategic employability.

To capture the diversity of governance and ownership models in the space sector, operators have been classified into distinct subcategories which reflect the spectrum that runs from purely institutional missions to fully private ones, with hybrid forms in between that combine public and commercial interests.

The selected categories are the following.

5.1.1 Public Operators

Public operators include governmental or intergovernmental institutions that fully fund, own and manage satellite missions. These entities typically develop space systems to pursue objectives of national interest, such as environmental monitoring, meteorology, communication, navigation or scientific research.
Examples include organizations like **NASA**, **NOAA**, **ESA** or the **European Commission's Copernicus Programme**, whose activities are financed and directed by state authorities or supranational bodies.

From a governance perspective, public operators are characterized by direct political oversight and the ability of the state to redefine or reallocate satellite use according to evolving priorities.
This flexibility, which is intrinsic to government-controlled assets, creates a latent strategic capability that distinguishes public missions from purely commercial or academic ones.
For this reason public operators are assigned a **score of 0.65** on the 0-1 scale, recognizing the high potential for strategic or defense-related use enabled by state ownership and control.
For instance, satellites from Copernicus or NOAA have been repeatedly used to support disaster response, maritime surveillance or situational awareness for military coordination.

5.1.2 Mixed Operators

Mixed operators represent hybrid governance structures that combine public and private participation in both funding and management.

They can arise through:

- **Public–Private Partnerships (PPPs)**,
- **joint ventures**,

- **shared-funding programs** where governmental agencies, industrial actors and research institutions collaborate on the same mission.

A prominent example is the United Kingdom's **Skynet programme**, where the Skynet 5 satellites are operated by Airbus Defence and Space under a long-term Private Finance Initiative (PFI) contract with the Ministry of Defence. Other relevant cases include systems developed through mixed governance such as **COSMO-SkyMed**, jointly funded by ASI and the Italian Ministry of Defence and the **OneWeb** constellation (Table 6.5), which operates under a shared ownership structure between private investors and the UK Government.
These governance models have become increasingly common in the modern space economy, as they allow governments to leverage private-sector innovation and investment while maintaining strategic influence over system design, tasking and data access. At the same time, private partners benefit from institutional stability and long-term contractual guarantees.

From a strategic perspective, mixed operators occupy the core of the dual-use spectrum: the involvement of private stakeholders ensures market driven considerations, but, since public actors retain partial authority, these systems can be repurposed or prioritized for defense when needed.

For these reasons, the Mixed category is assigned a **score of 0.5**.

5.1.3 Private Operators

Private operators include commercial companies that own, fund and manage satellites independently, primarily for market-oriented purposes. Their activities are driven by commercial interests such as telecommunications, Earth observation services, data analytics or broadband connectivity.
SpaceX (Starlink), **Planet Labs** or **Maxar Technologies** are emblematic examples, whose business models are based on service provision to private customers and institutional clients alike. These entities make decisions based on business goals, not national strategies.

Although private missions are generally designed for civilian or commercial markets, their technological capabilities and service flexibility can make them strategically relevant. For instance, high-resolution imagery from Planet Labs constellation or communication infrastructure from Starlink constellation have been used in military contexts, not because of direct defense ownership, but through government contracts, data-sharing agreements or emergency activations.

This demonstrates that commercial systems can indirectly support defense operations, meaning that private operators should be regarded as potential enablers of dual use rather than its direct implementers.

Reflecting this point, private operators are assigned a **score of 0.3**. This value indicates a predominantly civil orientation, acknowledging that while these actors operate in open markets, their assets can still become strategically relevant.
Their contribution to dual use is therefore context-dependent rather than intrinsic.

5.1.4 Academic Operators

Academic operators include schools, universities and research centers that develop and operate satellites for scientific or educational purposes. These missions are typically small-scale and are intended to advance research, train students or test new technologies under non-commercial and non-strategic conditions.
In fact examples include university cubesats and research satellites developed by institutions such as the University of **Tokyo**, **MIT** or **Politecnico di Milano** within academic or experimental programs.

From an institutional standpoint, academic missions are generally publicly funded but operate with academic autonomy and limited governmental involvement, since their goals focus on scientific progress and capacity building, not on operational or commercial exploitation.
Their contribution to national or defense capabilities is therefore indirect, just limited to the transfer of knowledge or technological spin-offs that may later be adopted in dual-use or military systems.
But the systems themselves do not possess the level of performance or operational reliability required for any defense applications.

For this reason, academic operators are assigned a **score of 0.15**, representing a predominantly non-strategic orientation.

5.1.5 Defense Operators

Defense operators are entities directly managed, owned, or controlled by national defense ministries, armed forces or intelligence agencies.
They are responsible for designing, funding, and operating satellites that serve explicitly military or security-related objectives, such as reconnaissance, surveillance, secure communications or early warning. Typical examples include the **U.S. National Reconnaissance Office (NRO)**, **United States Space Force (USSF)**, **France's DGA and CNES joint defense programs** or **China's Yaogan series**, as cited in the first paragraph of Chapter 4.
These missions are characterized by restricted data access, classified technical

details and dedicated military operational chains.
The strategic implications of defense-operated satellites are therefore explicit and unequivocal.

Given their exclusive military purpose and direct governmental control, defense operators are assigned a **score of 0.9**. This value represents the upper end of the dual-use spectrum, reflecting the purely strategic and operational intent of their missions.

*Nota: the upper end is 0.9 rather than 1 because the presence of the correction factor "Defense-Linked" which will be counted for every satellite under the Defense category, and so will take the final Index score to 1. Chapter 5.

5.1.6 Operator Summarizing Table

Table 5.1: Operator and Funding Scores

Operator Type	Score
Public	0.65
Mixed	0.50
Private	0.30
Academic	0.15
Defense	0.90

5.2 Primary User

The **Primary User** dimension identifies the dominant category of end-users who access and benefit from the satellite's services. This dimension is taken in consideration to understand the practical orientation of each mission, since the type of user ultimately determines how satellite data and capabilities are employed in real-world contexts.
While the operator controls ownership and governance, the user reflects the actual demand driving the system's functionality: whether it is scientific, commercial, institutional or defense-related.

In this model, the classification of primary users is thought to be based on the dominant user type associated with the satellite's main service market.
This means that, for systems serving multiple clients, the assessment follows a

principle of functional prevalence: the category is determined by who is the main end-user, regardless of the operator's nature.
For instance, a privately owned satellite that primarily serves government is classified as "Institutional User" (carrying a higher potential) even if the operator is a commercial entity.
While a privately owned satellite that primarily serves civilians, will be categorized as a "Commercial" or "Mass-Use" User, any defense-related structural component (such as dedicated divisions or government contracts) will then be captured by the "Defense Linked" flag.

Therefore by identifying the main beneficiary of the satellite's outputs, this dimension helps reveal how closely the system's utilization aligns with security or strategic objectives, complementing the governance-oriented perspective captured by the *Operator* dimension.
The following subcategories were defined to represent the full spectrum of user types.

5.2.1 Research

The **Research** category includes academic, scientific and non-profit organizations whose use of satellite data or services is oriented toward educational, environmental or purely scientific objectives.
These users typically include universities, research institutes and non-governmental organizations involved for instance in open-data initiatives or environmental monitoring.

Examples include **university cubesat programs**, **research-oriented networks** such as **CEOS (Committee on Earth Observation Satellites)**, the **United Nations Office for Outer Space Affairs (UNOOSA)**.

From an operational standpoint, these users do not pursue economic or strategic goals, but their activities are focused on innovation and societal benefit. For this reason in most cases the use of satellite data by this category is transparent and non-sensitive.
Thus even if their work can indirectly contribute to technological progress or innovations later adopted by governmental or industrial programs, their operational frameworks tend to emphasize civilian and peaceful use of space.

For these reasons, the Research user category is assigned a **score of 0.0** on the 0-1 scale, representing a purely civil orientation with no direct strategic implications.

5.2.2 Mass-Use

The **Mass-Use (Consumer-Oriented)** category refers to satellite services designed for the general public or large-scale civilian markets. These include infrastructures and applications that provide broadband connectivity, broadcasting or positioning services directly accessible to non-specialized users.
Representative examples are **GNSS systems** such as **GPS** and **Galileo**, as well as **commercial broadband constellations** like **Starlink** and **OneWeb**, which deliver communication or navigation services to millions of end-users worldwide.

From a functional perspective, this user group represents civilian mass demand, where the satellite system operates as a public utility or a commercial consumer product. Therefore, the users are individuals or private organizations with no direct link to institutional entities. However, given the essential nature of such infrastructures, their potential for indirect strategic relevance cannot be ignored. For instance, during crises or conflicts, communication or navigation networks serving civilians can be repurposed or prioritized for defense coordination, as demonstrated by Starlink's role in providing connectivity to Ukrainian forces in 2022.

In strategic terms, the Mass-Use category occupies a low but non-zero position on the dual-use spectrum. For these reasons, this subcategory has an assigned a **score of 0.25**.

5.2.3 Commercial

The **Commercial (Enterprise-Oriented)** category, instead, includes professional and industrial users that employ satellite data, products or services for business or operational purposes.
These users are typically private companies and service providers that purchase or integrate satellite-based capabilities into their commercial workflows (for instance in logistics, remote sensing, energy).
Representative examples include companies such as **Maxar Technologies**, **Planet Labs**, **ICEYE** and **SES S.A.**, whose customers consist largely of **business-to-business (B2B)**.

From a functional perspective, this category represents a professional demand, distinct from the mass consumer market: commercial users rely on satellites to generate value-added services, often using advanced data or customized infrastructures.
Strategically, Commercial users lie at the center of the dual-use spectrum because,

while their primary motivation is profit, their products and services can easily be integrated into defense or intelligence frameworks.

For these reasons, this category is assigned a **score of 0.5**, reflecting its inherently dual nature.

5.2.4 Institutional

The **Institutional** category includes governmental or intergovernmental organizations that use satellite systems for public service, administrative, scientific or security-support purposes.
These users encompass a wide range of national and supranational entities such as **ESA**, **NASA**, **ISRO** or **CNSA**, as well as agencies engaged in meteorology or environmental monitoring.

Institutional users operate within state or multilateral frameworks, where their activities are typically financed through public funds with objectives aligned to societal benefit and national interest.
Although their missions are primarily oriented toward non-military goals, they often involve dual infrastructures, shared data policies or inter-agency cooperation that enable indirect defense utility.
For example, satellites operated under civil space agencies may provide data for border surveillance, maritime awareness or disaster monitoring, that can be easily leveraged for strategic situational assessment. But most importantly, institutional users often maintain coordinated frameworks with defense or security institutions, facilitating access to restricted data when required.

For these reasons, since institutional users have high potential for dual or supportive use, a **score of 0.7** is assigned.

5.2.5 Defense

The Defense category includes national defense ministries, military forces and intelligence or security agencies that employ satellites directly for surveillance or strategic command purposes.
These users rely on satellite systems to support critical functions such as Intelligence, Surveillance and Reconnaissance (ISR), early warning, secure communications and navigation or targeting support.
Representative examples include the **U.S. Department of Defense** and the **National Reconnaissance Office (NRO)**.

Their mission requirements are explicitly strategic, designed to strengthen national defense, deterrence and situational awareness.

Strategically, this category represents the highest level of dual-use potential, reaching purely military utilization.

For these reasons, Defense Users are assigned a **score of 0.9**[1], representing the upper extreme of the dual-use spectrum.

5.2.6 Summarizing Table

Table 5.2: User Category and Score

Primary User	**Score**
Research / NGO	0.00
Mass-Use (Consumer-Oriented)	0.25
Commercial (Enterprise-Oriented)	0.50
Institutional	0.70
Defense	0.90

5.3 Purpose: Earth Observation

The **Earth Observation (EO)** category includes satellites designed to monitor, image or measure the Earth's surface and atmosphere, providing data for applications such as environmental monitoring, land-use analysis, disaster response and security observation.
EO systems collect data through various sensor technologies enabling continuous observation of terrestrial, oceanic and atmospheric processes. Because of their ability to produce both detailed and time-sensitive information, Earth Observation satellites are among the most versatile and widely used assets in the entire space sector.

From a strategic perspective, EO missions occupy a central position on the dual-use spectrum: although many of them are developed for civil or scientific purposes, their data can easily be repurposed for surveillance, reconnaissance and situational awareness. High-resolution imaging, in particular, provides valuable insights for defense planning, border control and intelligence operations, even when

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[1] The highest score assignable is 0.9 and not 1, because is the final index formula it will be summed to the "Defense-Linked" factor which has a maximum value of 0.1. Thus the two maximum scores combined will reach the highest value of 1.

produced by commercial or institutional satellites.
Therefore, EO systems inherently possess a medium-to-high dual-use potential, as the same sensors that support agriculture or environmental monitoring can also serve military objectives.

For this reason, the Earth Observation category is assigned a **score of 0.4** on the 0-1 scale.

Within this category, satellites are further subdivided into detailed purposes based on the **specific technologies they employ or**, in some cases, on **their primary operational function**.
Technological distinctions include systems using optical, radar (SAR), infrared or multispectral sensors, each of which statistically exhibits a different level of strategic potential, depending on the fields of application. In cases where a satellite carries multiple instruments or serves different functions, the most strategically significant capability was used as the reference for classification. This approach ensures that the evaluation remains consistent and representative, avoiding underestimation of systems that may have latent dual-use capabilities.
Finally, some EO missions are categorized by functional purpose (such as meteorology, environmental monitoring or surveillance) when their specialization prevails over a specific technological configuration.

The following subcategories have been selected [31], [32], [33].

5.3.1 Optical & Multi-spectral Imaging

Optical and multi-spectral imaging technologies exploit reflected sunlight in visible and near-infrared bands, producing detailed images of the Earth's surface. They are commonly used for land and vegetation mapping, urban planning, environmental monitoring and disaster assessment.
These missions typically employ CCD or CMOS cameras and multi-spectral sensors capable of distinguishing various surface features based on their spectral reflectance. Examples include **Planet Labs's Dove constellation (USA)**, Gaofen (China), **BalckSky (USA)**, **Sentinel-2 (ESA)**.

From a technical standpoint, optical and multispectral systems are among the most widespread and versatile observation technologies: their data is essential for civil applications such as agriculture, climate studies and infrastructure management. However, the same imagery is frequently used by intelligence and defense communities for mapping, reconnaissance and operational planning.
The relatively **high spatial resolution** (often below one meter) and the ability to detect surface changes over time make these sensors inherently dual-use in nature.

For example, civil imagery datasets can be cross-referenced with classified data to enhance intelligence assessments or to monitor conflict zones.
Nevertheless, optical systems are limited by cloud cover and daylight conditions, which somewhat reduce their value in continuous strategic operations compared to radar-based sensors.

For these reasons, Optical Imaging is assigned a **dual-use score of 0.5**.

5.3.2 Hyperspectral Imaging

Hyperspectral imaging collects data across hundreds of narrow, contiguous spectral bands, enabling the detection and identification of materials and surface features with extremely high precision.
Unlike multi-spectral systems, which capture a few discrete wavelength bands, hyperspectral sensors measure fine spectral signatures across the visible, near-infrared (VNIR) and shortwave infrared (SWIR) regions. This allows for detailed material characterization, such as identifying vegetation stress, soil composition, pollution and even camouflage materials.
Representative missions include **PRISMA (Italy)**, **Spark (China)**, **Zhuhai (China)**.

From a technical and operational standpoint, hyperspectral systems provide exceptional information depth since their spectral resolution enables users to distinguish between similar surface materials. Thus they can detect concealed infrastructure, camouflage or chemical residues being capable of supporting target identification and environmental intelligence in conflict zones. At the same time, their relatively small number and limited data accessibility prevent them from reaching the same operational ubiquity as radar-based surveillance systems.

For these reasons, Hyperspectral Imaging is assigned a **dual-use score of 0.55**.

5.3.3 Infrared (IR)

Infrared (IR) imaging detects emitted thermal radiation rather than reflected sunlight. They operate across mid-wave and long-wave infrared bands, allowing the measurement of surface temperature, thermal anomalies and fires both during the day and at night [34].

From a civil perspective, IR satellites are indispensable tools for environmental observation, agriculture and natural hazard detection since they provide early warning information for wildfire outbreaks and droughts, supporting climate resilience and public safety.
However, the same ability to detect heat emissions also makes them strategically

valuable since infrared data can reveal military installations, active engines and missile launches, even when these are concealed from optical sensors. Their night-time observation capability and independence from sunlight make them particularly suited for continuous situational awareness and target tracking.
Some notable examples, in fact, include **SBIRS GEO - Space Based Infrared System Geosynchronous (USA)**, **SPIRALE - Système Préparatoire Infra-Rouge pour l'Alerte (France)**, **DSP - Defense Support Program (USA)**, but also **HotSat-1 (ESA)**.

For these reasons, Infrared (IR) Imaging is assigned a **dual-use score of 0.6**.

5.3.4 Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar (SAR) and other **microwave imaging systems** actively emit radar signals and measure the energy reflected from the Earth's surface. Unlike optical or infrared sensors, they can operate day and night and are largely unaffected by cloud cover or weather conditions, ensuring continuous data acquisition. SAR satellites measure surface deformation, ocean currents, sea ice and are also capable of detecting moving targets.
Typical payloads include X-band, S-band or C-band radar systems, as seen in missions such as Sentinel-1 and Capella Space [35], [36], [37].
Some example of satellites which use SAR systems are **ICEYE constellation (Finland)**, **COSMO-Skymed (Italy)**, **Capella (USA)**, **Yaogan (China)**.

From a technical perspective, SAR represents one of the most advanced and strategically significant observation technologies: it has the ability to detect surface changes with centimeter-level accuracy and to image through darkness and atmospheric conditions.
For these reasons the same capabilities which supports disaster management are directly applicable to target tracking, ship detection and battlefield monitoring.

Synthetic Aperture Radar (SAR) is assigned a **dual-use score of 0.7**, the highest within the Earth Observation detailed purposes sensors.

5.3.5 Radio Frequency Signals (RF)

Radio Frequency (RF) payloads detect and analyze radio emissions originating from Earth's surface [38], [39]. Unlike active sensors such as radar, this systems are passive and rely on the interception of existing electromagnetic signals. These missions are designed to monitor radio frequency activity, supporting applications like ship and aircraft tracking (AIS), spectrum management and telecommunication monitoring [40].
Typical payloads include RF receivers and specialized antennas, as used in missions

such as **HawkEye 360 (USA)**, **BRO - UnseenLabs (France)**, **Lemur - Spire Global (USA)**, **STRO-AIS (Russia)**.

From a civil perspective, RF observation contributes to aviation and maritime safety along with global logistics monitoring. However, since RF systems can also detect non-cooperative emitters, they possess an inherent intelligence-gathering capability that allow them to monitor for example military communications or electronic signals. In practice, several RF observation satellites are already integrated into defense information networks or provide services directly to national security agencies.

Strategically, this technology occupies a highly dual-use position a **score of 0.65** is assigned. This value reflects its high strategic significance, especially in maritime and electromagnetic situational awareness, while acknowledging its continued use in civil safety and communication monitoring domains.

5.3.6 Video Imaging

Satellites with **Video imaging** services are equipped with high-frame-rate optical sensors which are capable of capturing continuous motion sequences rather than static images. Unlike traditional optical or multi-spectral systems, which provide periodic snapshots, video satellites generate real-time or near real-time footage of dynamic events on the Earth's surface. This enables the monitoring of moving targets, traffic flows, infrastructure activity and short-term environmental changes. Representative examples include **Jilin Video satellites (China)** and **Zhuhai (China)**.

From a civil perspective, video satellites are used for urban planning or transport management, since the continuous data stream they provide is valuable for understanding behavioral patterns and temporal evolution in monitored regions. However, the same capability also makes them strategically significant: real-time observation of ground activity has clear applications for border surveillance and tactical reconnaissance. In fact continuous imaging allows for the detection of vehicle movement, troop deployment, but also infrastructure operation, even in the absence of other surveillance assets.

For these reasons, Video Imaging is assigned a **dual-use score of 0.55**, which reflects its balanced character.

5.3.7 Meteorology

Meteorology satellites are designed to observe atmospheric conditions: they collect key environmental variables such as temperature, humidity, cloud cover

and precipitation, supporting weather forecasting, environmental monitoring and scientific research.
These systems typically operate in geostationary or polar orbits, combining continuous regional coverage with global datasets.

Strategically, this category presents a low but non-zero dual-use potential. Although meteorological data is predominantly civil and often distributed under open-access policies, it remains a critical enabler for military planning: weather and environmental information is essential for navigation and flight scheduling. Defense meteorological services historically integrate such data to support mission readiness. However, the systems themselves are not designed for direct intelligence or tactical functions.

For these reasons, it is assigned a **dual-use score of 0.35**.

5.3.8 Earth Science

Earth Science satellites focus on the observation of terrestrial, oceanic and atmospheric processes with the primary aim of supporting environmental research, ecosystem monitoring and resource management.
These missions are typically developed and operated by civilian space agencies and are frequently structured around open-data principles that encourage scientific collaboration and international transparency.

Although their data can indirectly support defense operations by providing terrain characterization and mobility assessments. Considering these characteristics, Earth Science is assigned a **dual-use score of 0.20**.

5.3.9 ISR

The **Intelligence, Surveillance and Reconnaissance (ISR)** category includes satellites explicitly designed to support intelligence and security operations through the acquisition and transmission of information on activities occurring on Earth's surface or in orbit. These systems provide real-time situational awareness, enabling the detection of strategic targets such as military installations or vehicle movements. Representative examples include the **USA's NRO reconnaissance constellations** and **China's Yaogan**.

ISR missions integrate a wide range of observation and interception technologies:

- Optical and video surveillance for high-resolution imaging;
- Synthetic Aperture Radar (SAR) for day-and-night;

- Signals Intelligence (SIGINT) and Electronic Intelligence (ELINT) for detecting radio or electronic emissions;
- infrared payloads for heat and missile launch detection.

From a strategic perspective, ISR satellites constitute the core of space-based defense infrastructure. They play a crucial role in early warning, threat assessment, targeting support and battlefield monitoring, directly contributing to a state's operational readiness and deterrence posture. Their outputs feed into integrated command-and-control systems, supporting both national and allied intelligence frameworks..

ISR satellites are positioned near the purely strategic end of the spectrum with a **dual-use score of 0.85**, recognizing that while these systems occasionally share technical foundations with civil observation missions, their main function and design are intrinsically strategic and defense-driven.

5.3.10 Earth Observation Summarizing Table

Detailed Purpose	**Score**
Optical/Multi-spectral Imaging	0.50
Hyperspectral Imaging	0.55
Infrared (IR)	0.60
SAR (Synthetic Aperture Radar)	0.70
RF (Signal-based Observation)	0.65
Video Imaging	0.55
Meteorology	0.35
Earth Science	0.20
ISR (Intelligence, Surveillance, Reconnaissance)	0.85

Table 5.3: Detailed Purpose and Dual-Use Score for Earth Observation Satellites

5.4 Purpose: Communication

Communications satellites provide connectivity for voice, data, video and command links across all domains. They in fact, enable services ranging from consumer broadband and broadcasting to secure command-and-control and data relay for space and ground networks. Because the same infrastructure can support both public services and mission-critical operations, communications systems sit near the middle–upper range of the dual-use spectrum.

For the general Purpose category, Communications is assigned a **score of 0.55**. This reflects a predominantly civil and commercial orientation, while acknowledging the substantial strategic value of space-based connectivity for crisis response, military mobility and secure command links.

Unlike Earth Observation, where sensor types (optical, SAR, IR, etc.) more clearly correspond to different levels of strategic sensitivity, the dual-use potential of communications satellites is better understood through their functional roles. For this reason, the detailed purposes have been designed as a functional classification, reflecting the type of service provided and the operational characteristics typically associated with specific frequency bands, payload configurations and network architectures:

- services that operate on protected or jam-resistant bands and include encryption / anti-jamming features;
- services defined by throughput and coverage model (broadband HTS, broadcast, narrowband IoT/M2M);
- mobility services (maritime, aeronautical);
- data relay / inter-satellite links (ISL) enabling secure, low-latency transport between spacecraft and to ground.

This functional subdivision is more informative for dual-use assessment in communications, because it aligns directly with who can use the service, how it is used operationally and how resilient and secure it is [31].

5.4.1 Secure Communication

Secure Communications systems provide encrypted and jam-resistant links used mainly by military forces, government users and critical national infrastructure. They operate across protected frequency bands such as X-band, UHF or EHF, which are specifically allocated for defense and governmental use. These systems are engineered to guarantee high resilience, global coverage and confidentiality of data links, ensuring operational continuity even in hostile or degraded environments. Representative missions include **Skynet (U.K.)** [41], **AEHF (USA)**, **Rodnik (Russia)** and **Syracuse IV (France)**: all key pillars of national and allied defense communication architectures.

Strategically, secure communication satellites are indispensable for defense coordination and, since communication infrastructure underpins all modern defense operations, the loss or degradation of these assets would immediately impact national resilience and deterrence capabilities.

For these reasons, Secure Communications is assigned a dual-use **score of 0.9**[2], reflecting its exclusive defense ownership and control.

5.4.2 IoT & M2M Communications

Internet of Things (IoT) and Machine-to-Machine (M2M) communications satellites provide low-data-rate connectivity for a vast number of small and often autonomous devices distributed across the globe. These systems typically operate in narrow-band, L-band or S-band, frequencies and are optimized for low power

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[2] The highest score assignable is 0.9 and not 1, because is the final index formula it will be summed to the "Defense-Linked" factor which has a maximum value of 0.1. Thus the two maximum scores combined will reach the highest value of 1.

consumption, wide coverage and simple terminal architecture. Their services are essential for linking sensors, vehicles, remote assets or monitoring platforms, supporting applications in logistics, environmental monitoring, precision agriculture and smart infrastructure management [42].
Representative missions include **SpaceBEE - Swarm Technologies (USA)**, **Astrocast (Switzerland)**, **Kepler (Canada)**.

They are part of a growing ecosystem connecting industrial and environmental applications. In fact their payloads generally lack the high bandwidth or encryption capabilities required for strategic communication, focusing instead on scalability and cost-efficiency. However, their global coverage and capacity to connect autonomous or remote sensors introduce potential dual-use scenarios, such as situational awareness, logistics tracking or infrastructure monitoring in defense-related contexts. For example, the same IoT constellations used for commercial fleet management could, in principle, be adapted to support battlefield asset tracking or environmental reconnaissance.

Despite this, the open architecture and low-security protocols typical of these networks restrict their use in classified or critical missions and accordingly a **dual-use score of 0.3** is assigned.

5.4.3 Wideband Communications

Wideband Communications satellites provide high-throughput connectivity for broadband internet, multimedia broadcasting and data transmission services across large regions or globally. These systems typically operate in Ka-band, Ku-band and C-band frequencies, using high-throughput payloads (HTS) and spot-beam architectures to maximize data capacity and efficiency.
They serve a wide range of civil, commercial and governmental users, enabling broadband internet access, television broadcasting, corporate networks and remote connectivity for infrastructure or transportation sectors.
Representative missions include the commercial **Starlink (USA)**, **OneWeb (UK)**, **ViaSat-3 (USA)** and military **WGS - Wideband Global Satcom (USA)**.

Wideband satellites form the backbone of global communications infrastructure, extending broadband access to regions where terrestrial connectivity is limited or unavailable. However the capability to establish high-speed, long-distance links also grants them strategic value, especially in supporting remote military bases and maritime fleets where resilient and flexible communications are critical.
Thus, this category represents a transitional zone between civil and dual-use applications. Although primarily designed for mass-use and commercial markets, their wide coverage and scalable capacity can be strategically leveraged: the same

infrastructure can be rapidly adapted or contracted for defense communications, especially when enhanced with encryption or bandwidth prioritization mechanisms.

Recent examples, such as the use of commercial constellations like Starlink in military theaters, have demonstrated how wideband networks can rapidly shift roles from civilian connectivity to operational support, providing real-time communication for field units or command networks.

For these reasons, Wideband Communications (Internet & Broadcast) is assigned a **dual-use score of 0.4**.

5.4.4 Mobile Satellite Services (MSS)

Mobile Satellite Services (MSS) provide voice and data connectivity to mobile users, including ships, aircraft and ground vehicles and handheld terminals. These systems typically function in L-band and S-band frequencies, which offer reliable signal penetration through clouds, rain and foliage, ensuring stable communication in a wide range of operational environments.
Representative examples include **Inmarsat (USA)**, **Iridium Next (USA)** and **Globalstar (UK)**.

MSS systems operate via dedicated LEO or MEO constellations offering persistent global coverage, low latency and real-time communication capabilities that support aviation, maritime operations, emergency response and field logistics. Although primarily aimed at civilian and commercial users, their ability to deliver secure and continuous communication where terrestrial networks are unavailable makes them inherently dual-use. For this reason, defense and government organizations routinely rely on commercial MSS services which include dedicated features like encrypted or prioritized access to support operational needs.

Accordingly, Mobile Satellite Services (MSS) are assigned a **dual-use score of 0.5**.

5.4.5 Data Relay / Inter-Satellite Link (ISL)

Data Relay and Inter-Satellite Link (ISL) systems enable direct communication between satellites or between satellites and dedicated relay nodes, allowing for continuous and near real-time data transfer, without depending exclusively on ground stations. These systems typically employ radio-frequency (RF) or laser communication links (optical ISL) to transmit data with high speed and low latency.
Representative missions include the European Data Relay System (EDRS), **DRSS - Tracking and Data Relay Satellite (USA)**, and newer optical communication constellations such as Space Development Agency (SDA) Tranche 1 Transport

Layer or **Starlink's laser-linked network**.

Those systems enable spacecraft to exchange information directly, creating autonomous communication networks that operate independently of ground coverage. By routing large volumes of data instantly between satellites, they enhance situational awareness, support continuous Earth-observation missions, but most importantly they improve system responsiveness enabling reliable coordination across entire constellations.
Their ability to provide secure, uninterrupted connectivity also makes them increasingly relevant for defense and intelligence activities: high-speed optical ISLs, for instance, reduce detectability and interception risks, making them suitable for classified or tactical communication flows.

For these reasons, Data Relay / Inter-Satellite Link (ISL) is assigned a **dual-use score of 0.6**.

5.4.6 Communication Summarizing Table

Detailed Purpose	**Score**
Secure Communications	0.9
IoT & M2M Communications	0.3
Wideband Communications (Internet & Broadcast)	0.4
Mobile Satellite Services (MSS)	0.5
Data Relay & Inter-Satellite Link (ISL)	0.6

Table 5.4: Detailed Purpose and Dual-Use Score for Communication Satellites

5.5 Purpose: Navigation

Navigation satellites provide global positioning, navigation and timing (PNT) services that enable accurate geolocation and synchronization across civil, commercial and defense domains. These systems form the backbone of modern infrastructures, supporting transportation, telecommunications, finance, energy and military operations. Because they serve both open civil users and secured military channels, they represent one of the most balanced examples of dual-use technology.

From a strategic standpoint, PNT systems are indispensable for national autonomy and operational sovereignty. They ensure precise timing and positioning for critical applications such as air traffic management, emergency response and guided weapon systems, while also supporting everyday activities like smartphone navigation and financial transactions. Their dual-signal architecture combines public open services and encrypted or restricted military bands.

For this reason, the Navigation purpose as a whole is assigned a **dual-use score of 0.5**, reflecting its perfectly hybrid nature.

5.5.1 Global Navigation

Global Navigation Satellite Systems (GNSS) provide worldwide PNT coverage, enabling continuous positioning and time reference for users anywhere on Earth [43].
The major global constellations, **GPS (USA)**, **GLONASS (Russia)**, **Galileo (EU)** and **BeiDou (China)**, all operate multiple orbital planes of medium Earth orbit (MEO) satellites that transmit open and encrypted signals across multiple frequencies.

GNSS constellations support a wide range of civil applications, from aviation and maritime navigation to telecommunications synchronization and emergency management while simultaneously incorporating encrypted and access-controlled military channels (such as the P(Y)-code, M-code or PRS). This dual-channel architecture allows states to guarantee secure guidance, operational control and protection against spoofing or interference.

Beyond their technical role, global PNT systems function as strategic assets. Managing an independent GNSS provides assured access to navigation and timing services even during crises and it especially grants states a degree of geopolitical leverage over actors reliant on foreign constellations.

This coexistence of open civilian services and restricted military capabilities makes GNSS one of the most emblematic examples of dual-use space infrastructure and therefore a **dual-use score of 0.5**.

5.5.2 Regional Navigation

Regional Navigation systems provide PNT coverage over specific geographic areas, often developed to complement or reduce reliance on foreign GNSS networks. Examples include **NavIC - Indian Regional Navigation Satellite System (India)**, **QZSS - Quazi-Zenith Satellite System (Japan)**. These systems typically consist of a smaller number of satellites operating in geostationary or inclined orbits, optimized to enhance regional accuracy and resilience.

At the strategic level, regional PNT systems function as tools of autonomy and security policy since they allow states to maintain continuity of navigation and timing services in the event of signal denial or geopolitical tensions affecting global constellations. Although their day-to-day use is largely civil, as the global services, their strategic intent and integration into national defense frameworks are explicit.

For these reasons, Regional Navigation is also assigned a **dual-use score of 0.5**.

5.5.3 Navigation Summarizing Table

Detailed Purpose	**Score**
Global Navigation	0.5
Regional Navigation	0.5

Table 5.5: Detailed Purpose and Dual-Use Score for Navigation Satellites

5.6 Purpose: Technology

The **Technology** category includes satellites designed to test, validate or mature new technologies in orbit before they are integrated into operational missions. These spacecraft serve as experimental platforms.
While most of these missions originate in academic or institutional research contexts, others are conducted by industry partners aiming to raise the technological readiness of components for commercial or strategic applications.

From a general perspective, technology demonstration satellites occupy a low-to-moderate position on the dual-use spectrum. Their primary goal is to verify functionality and performance, not to deliver operational capabilities. However, the knowledge and systems they validate often become foundational for both civil and defense programs, making this purpose an indirect but crucial driver of strategic innovation.
For this reason, the Technology Demonstration purpose as a whole is assigned a dual-use score of **0.3**, indicating a mainly civil orientation but with a latent potential to enable future dual-use or defense technologies once maturity increases.

This macro category was then divided in two distinct Detailed Purpose.

5.6.1 Research

This subcategory includes research-oriented or experimental missions focused on early-stage technological validation, typically characterized by **low Technology Readiness Levels (TRL 1–4)**.
These projects are often led by universities, research institutes or public laboratories with academic or scientific objectives.
Examples include small satellites testing new materials, basic sensor prototypes or scientific payloads without direct operational or defense intent.

From a strategic standpoint, these missions have minimal direct dual-use potential, as they primarily aim to prove scientific concepts rather than deliver deployable systems. Their results contribute to the advancement of knowledge and may indirectly influence future technological progress, but they generally lack immediate military or commercial exploitation pathways.
For these reasons,it is assigned a **dual-use score of 0.2**, reflecting its purely scientific orientation and low short-term strategic impact.

5.6.2 Advanced Technology Demonstration

This subcategory refers to missions developing or validating technologies at **medium-to-high maturity levels (TRL 5–8)**.
They are typically conducted in industrial or pre-operational contexts, often involving public–private partnerships or government-funded programs.
These satellites test flight-ready prototypes, such as advanced sensors, propulsion systems or secure communication payloads, with the goal of transitioning to operational deployment once successful.
Some example mantioned in the dataset are **Unicorn (UK)**, **CSIM-FD (Compact Spectral Irradiance Monitor - Flight Demonstration)**.

Strategically, these missions can represent a critical bridge between research and application: when demonstrations succeed, the validated technologies can be rapidly integrated into operational systems. Although not military missions per se, they constitute an important phase of dual-use technology maturation, frequently financed or supervised by national or international space agencies.

For these reasons, it is assigned a **dual-use score of 0.4**, acknowledging its higher strategic potential compared to early-stage research.

5.6.3 Technology Summarizing Table

Detailed Purpose	Score
Research	0.2
Advanced Technology Development	0.4

Table 5.6: Detailed Purpose and Score for Technology

5.7 Purpose: Space Observation

The Space Observation purpose encompasses satellites and instruments dedicated to observing celestial bodies, cosmic phenomena and space environments beyond Earth's atmosphere.
This category primarily includes astronomy missions and space situational awareness (SSA) systems, covering both scientific research and space monitoring functions. While the core of this segment is scientific, with the goal of expanding knowledge of the universe, certain observational technologies also support strategic applications, such as space traffic management, debris tracking or counter-space operations.
In general, space observation systems are characterized by highly advanced sensors and they generate fundamental data for astrophysics and planetary science, but can also contribute indirectly to national security by improving orbital awareness and space domain control.

For this reason, the Space Observation purpose as a whole is assigned a **dual-use score of 0.3**, reflecting its predominantly scientific orientation but acknowledging its growing strategic relevance in the context of space surveillance and defense preparedness.

5.7.1 Astronomy

The **Astronomy** subcategory includes satellites and space telescopes dedicated to the study of celestial objects and cosmic phenomena.
These missions observe the universe across multiple wavelengths (optical, infrared, ultraviolet, X-ray, gamma-ray and radio) with the primary goal of advancing scientific understanding of stars, galaxies, black holes and cosmic radiation.
Representative examples include the **Hubble Space Telescope (NASA/ESA)**, **Fermi (NASA)**, **HXMT (Hard X-ray Modulation Telescope, Insight) (China)**.

Their data are typically open-access, shared within the international scientific community, and rarely associated with restricted or classified applications.
For these reasons, Astronomy is assigned a **dual-use score of 0.15**, representing a purely scientific purpose with minimal strategic implications.

5.7.2 Space Surveillance

The **Space Surveillance** subcategory includes missions designed to observe objects in Earth's orbit and the broader space environment. These systems monitor satellites, debris and near-Earth objects (NEOs), providing critical data for collision avoidance, orbital management and space situational awareness (SSA). Representative examples include the **U.S. Space-Based Space Surveillance (SBSS) system**, **GSSAP 2 (Geosynchronous Space Situational Awareness Program, USA 254)**, **Skylark (Canada)** and Russian and Chinese optical tracking satellites.

From a technical perspective, these satellites employ high-precision optical sensors and wide-field cameras to detect and characterize space objects. Although many SSA systems are mainly operated international organizations, their applications extend into strategic and defense domains, where they are used for satellite identification, threat detection and tracking of potential adversary assets. In some cases, the same technology forms the basis for counter space capabilities, including ASAT targeting support or inspection satellites capable of close-proximity maneuvers.

Strategically, space surveillance represents a critical element of national security and therefore, in line with this analysis, it has been classified as part of the ISR category, with a **dual-use score of 0.85**.

5.7.3 Space Observation Summarizing Table

Detailed Purpose	**Score**
Astronomy	0.15
Space Surveillance (ISR)	0.85

Table 5.7: Detailed Purpose and Dual-Use Score for Space Observation

5.8 Orbit Class

The Orbit Class dimension refers to the altitudinal and functional category of a satellite's orbit, which in most cases determines its operational role and visibility. Different orbital regimes usually correspond to distinct mission profiles because each orbit type offers specific advantages in terms of coverage or latency so the choice of orbit is often decided upon the mission intent.
From a dual-use perspective, orbit class can be a relevant indicator of potential strategic relevance: lower orbits are typically associated with commercial and observation activities, while higher orbits are favored for defense, navigation or continuous monitoring missions [44], [45]. For this reason, this dimension captures how orbital placement itself can reflect the degree of militarization or strategic utility of a satellite system.

The macro categories of orbits taken in consideration are the following.

5.8.1 LEO

Altitude: 200–1,200 km

Low Earth Orbit is the most widely used orbital regime, hosting the majority of modern constellations dedicated to Earth observation and communications.
Examples include **Starlink**, **Planet Labs**, **ICEYE** and **Sentinel** missions.

From a strategic standpoint, LEO offers high spatial resolution for imaging and low latency for communication, bit also rapid revisit times, making it ideal for both civil and military applications.
It supports a large number of dual-use systems, from commercial Earth observation to SIGINT constellations.
Given its balanced role across civil and defense sectors, LEO is assigned a **score of 0.5**, reflecting its highly dual-use nature.

5.8.2 MEO

Altitude: 2,000–35,000 km

Medium Earth Orbit hosts primarily navigation and timing constellations such as **GPS**, **Galileo**, **GLONASS** and **BeiDou**.
It provides global and continuous coverage: assets that are essential for both civil infrastructure and military operations.

From a strategic viewpoint, the PNT function has become a critical defense capability, supporting missile guidance, fleet coordination and timing synchronization. Although civil users rely on the same constellations through open signals, the presence of encrypted channels for defense tilts MEO's profile slightly toward the strategic side.

Therefore, MEO is assigned a **dual-use score of 0.55**, indicating a predominantly dual-use nature.

5.8.3 GEO

Altitude: 35,786 km

Geostationary Orbit allows satellites to remain fixed relative to the Earth's rotation, providing continuous coverage over a specific region[3].
It is widely used for communications and defense command systems: representative missions include commercial GEO telecommunication satellites as **Intelsat (USA)** or **Eutelsat (Europe)** and military relay systems like **AEHF (USA)**.

Strategically, GEO is a prime location for persistent surveillance and secure communications, making it a core component of national security architectures. It has the ability to host large, high-power payloads and monitor vast geographic areas gives it strong military value.

For this reason, GEO is assigned a **dual-use score of 0.65**, reflecting its significant defense relevance while maintaining extensive civil use through meteorological and broadcast missions.

5.8.4 HEO

Apogee: Very high (typically 30,000–40,000 km or more)

Highly Elliptical Orbits are characterized by long dwell times over polar or high-latitude regions, making them ideal for continuous surveillance and early-warning missions.
Representative systems include **Sirius (USA)**, **EKS Tundra (Russia)** and Molniya-type orbits used historically for communication and ISR coverage of northern areas.

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[3] Because GEO is, by definition an equatorial orbit, this characteristic is intrinsic to the orbit type and does not require separate specification in the classification scheme; it is already accounted for in the scoring logic used in this study.

HEO orbits are strategically optimized for defense applications, allowing persistent visibility over regions not easily covered by GEO satellites. They are primarily used for missile detection and electronic intelligence.
Due to this clear military orientation and limited civil application, HEO is assigned a **dual-use score of 0.75**, positioning it near the upper end of the strategic spectrum.

5.8.5 Orbit Class Summarizing Table

Orbit	Score
LEO (Low Earth Orbit)	0.50
MEO (Medium Earth Orbit)	0.55
GEO (Geostationary Orbit)	0.65
HEO (Highly Elliptical Orbit)	0.75

Table 5.8: Orbital Class and Dual-Use Score

5.9 Orbit Type

The Type of Orbit dimension specifies the geometric configuration and inclination of a satellite's trajectory around Earth.
While the orbit class determines altitude and general operational region, the orbit type defines revisit frequency and observation geometry which are parameters that directly influence the mission's purpose and strategic potential [46].

5.9.1 Polar

Polar orbits allow satellites to pass over the entire globe, offering complete planetary coverage. They are commonly used for Earth observation and environmental monitoring, but since this configuration provides regular revisit times it is also ideal for strategic surveillance and mapping.
Representative examples are **Sentinel-1 / Sentinel-2 (ESA Copernicus)** and Radarsat-2 (Canada).

Because of their balanced use by civil and intelligence satellites, polar orbits are assigned a **score of 0.55**, reflecting their highly dual-use nature.

5.9.2 Sun-Synchronous (SSO)

A Sun-Synchronous Orbit maintains a constant local solar time over each pass. In this way it ensure consistent lighting which is a key requirement for optical Earth observation, making it the standard orbit for imaging missions, both civil and military.
SSO is used by systems such as **Landsat-8 (NASA/USGS)**, **KOMPSAT-3/5 (South Korea)** and spy satellites requiring uniform illumination for change detection.

Because civil and defense missions share this orbital regime almost equally, SSO is assigned a **score of 0.5**, representing perfect dual-use equilibrium.

5.9.3 Equatorial

Equatorial orbits (excluding GEO, for which the equatorial geometry is intrinsic and already accounted for in the dedicated GEO scoring) cover regions along the equator, optimizing communication and environmental monitoring in low-latitude areas.
They are particularly useful for telecommunication and meteorology, but offer limited strategic coverage, especially at higher latitudes.

Therefore, these orbits are mostly commercial or civil in nature and accordingly they are assigned a **dual-use score of 0.3**, indicating low military relevance.

5.9.4 Non-Polar Inclined

Non-polar inclined orbits have moderate inclinations, providing regional coverage but not full global visibility. They are often chosen for communication and occasionally used by military payloads for regional surveillance or relay: these orbits remain predominantly civil.

Therefore, a **score of 0.35** reflects their limited but plausible dual-use potential.

5.9.5 Molnyia

Molniya orbits are a specialized class of highly elliptical trajectories designed to provide prolonged visibility over high-latitude regions, such as Russia or the Arctic. They are widely used for military early warning, like **EKS (Russia)**. Because their geometry favors persistent observation and data relay in polar regions, Molniya orbits are predominantly strategic.
Accordingly, they are assigned a **dual-use score of 0.8**, placing them near the military end of the spectrum.

5.9.6 Orbit Type Summarizing Table

Subtype	**Parent Orbit**	**Score**
Polar	LEO	0.55
Sun-Synchronous (SSO)	LEO	0.50
Equatorial	- -	0.30
Non-Polar Inclined	LEO/MEO	0.35
Molniya	HEO	0.80

Table 5.9: Orbital Type and Dual-Use Scores

Chapter 6

Construction Of The Dual-Use Index

This chapter describes the final stage of the methodological framework: the construction of the Dual-Use Index.
After defining and scoring each analytical dimension in Chapter 5, the next step involved integrating all these variables into a single measurable indicator.
To build the model, a structured Excel dataset was developed, where each satellite entry includes one column for every dimension's score, corresponding to the categories introduced in Chapter 4 (*Operator, Defense-Linked factor, Primary User, Purpose, Detailed Purpose, Orbit Class and Orbit Type*). For each of these dimensions, the assigned numerical values reflect the degree of dual-use potential as defined through the qualitative–quantitative translation process.
Finally, a dedicated column was added to compute the final composite score, obtained through a weighted formula that combines all the partial scores into a single Dual-Use Index value. This final computation will be described in detail in the following sections.

6.1 Weighting Method and Index Composition

The weighting scheme was designed to reflect the relative importance of each dimension in determining a satellite's overall dual-use potential.
Each factor contributes differently to the final score, depending on how directly it influences a system's strategic applicability or operational flexibility.

The weights were distributed as follows:

Dimension	**Weight**
Operator	0.20
Primary User	0.20
Purpose	0.10
Detailed Purpose	0.30
Orbit Class	0.10
Orbit Type	0.10
Defense-Linked	+0.10

Table 6.1: Weight distribution for each analytical dimension in the Dual-Use Index.

The selected weights follow a logic that prioritizes the dimensions most closely associated with strategic intent and mission sensitivity.
In particular, *Detailed Purpose* and *Operator* receive the highest coefficients because they capture the clearest signals of whether a satellite has been conceived with dual-use or defense-oriented functions. Lower weights are assigned to orbital characteristics, which influence operational flexibility but provide only indirect evidence of defense relevance.
The Defense-Linked correction factor was then added with the value of +0.10.

The final Dual-Use Index was thus computed according to the following weighted aggregation formula:

$$\begin{aligned}\textbf{Dual-Use Index} = \Big[&(\text{Operator} \times 0.2) + (\text{Primary User} \times 0.2) + (\text{Purpose} \times 0.1)\\ &+ (\text{Detailed Purpose} \times 0.3) + (\text{Orbit Class} \times 0.1)\\ &+ (\text{Orbit Type} \times 0.1)\Big] + \text{Defense-Linked Factor}\end{aligned}$$

The resulting value, rounded to two decimal places, provides a numerical score between 0 and 1, where following the previous logic:

- **0** represents a purely civil satellite,
- **1** represents a fully military satellite and
- intermediate values capture varying degrees of dual-use integration.

Although more advanced modelling techniques could capture interactions or non-linear effects, the chosen additive structure offers a clear and transparent balance between analytical precision and ease of interpretation.
At the same time, the weighting scheme has been designed to remain fully modular, allowing the model to evolve as new satellite typologies emerge or as additional parameters, such as maneuverability, autonomy, encryption sophistication or sensor resolution, become available. This flexibility ensures that the index can be progressively refined to reflect technological developments and the changing dynamics of the global space environment.

6.2 Example od Score Combination

To illustrate how the Dual-Use Index is computed in practice, this section presents a set of representative examples drawn from different mission types, operators and generations of satellite systems.
Each table corresponds to an individual row extracted from the Excel dataset specifically compiled for this thesis and therefore includes satellite-specific identifiers such as the mission code, launch date and constellation generation. Although the entries refer to single satellites, many of these missions belong to larger constellations in which all units share identical or nearly identical characteristics. For this reason, the associated scores and comments should be interpreted as representative of the entire satellite family rather than of a single spacecraft.

Each example shows how the individual dimension scores such as *Operator*, *Primary User*, *Purpose*, *Detailed Purpose* and the *Defense-Linked Factor* are combined through the weighted formula to produce the final index value.
By comparing satellites that belong to different categories, or even different generations of the same constellation, it becomes possible to observe how specific technical features, institutional arrangements or defense-oriented links influence the final dual-use score. The following summaries therefore serve not only as practical demonstrations of the scoring model but also as evidence of how the index captures variations in strategic potential across a diverse set of missions.

Starlink Constellation - Comparing Generations

A clear example of how the scoring model captures differences in strategic potential is provided by the evolution of the Starlink constellation.
The earliest versions, such as **Starlink V1.0** (Table 6.2), were conceived primarily as commercial broadband satellites with no defense links and limited functional complexity. As a result, their Dual-Use Index remains relatively low.
The intermediate generation **Starlink V1.5** (Table 6.3), introduces incremental operational improvements and, in some cases, establishes formal defense-linked partnerships, which modestly raise the final score.
The shift becomes more evident with the **Starlink V2-Mini** generation (Table 6.4), where enhanced technological capabilities, such as integrated data-relay functions, and confirmed connections with defense users lead to a higher dual-use value.
Comparing these generations demonstrates how even within a single commercial constellation, changes in design, capability and institutional relationships can significantly alter the strategic profile of the system.

Parameter	**Assigned Value**
Name of Satellite	Starlink-2413
Country of Operator/Owner	USA
Operator/Owner Name	SpaceX
Date of Launch	11/03/2021
Operator & Fundings	Private
Defense & Intelligence Link	**No**
Primary Users	Mass-Use
Purpose	Communications
Detailed Purpose	**Internet Broadband Communication**
Comments	**Starlink V1.0**
Class of Orbit	LEO
Type of Orbit	Non-Polar Inclined
Operator Score	0.30
Defense-Linked Factor	- -
Primary User Score	0.25
Purpose Score	0.45
Detailed Purpose Score	0.40
Orbit Class Score	0.50
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.38**

Table 6.2: Starlink Generation V1.0 - Satellite Summary

Parameter	**Assigned Value**
Name of Satellite	Starlink-3281
Country of Operator/Owner	USA
Operator/Owner Name	SpaceX
Date of Launch	18/12/2021
Operator & Fundings	Private
Defense & Intelligence Link	**Yes**
Primary Users	Mass-Use
Purpose	Communications
Detailed Purpose	**Internet Broadband Communication / Data Relay**
Comments	**Starlink V1.5**
Class of Orbit	LEO
Type of Orbit	Non-Polar Inclined
Operator Score	0.30
Defense-Linked Factor	+0.10
Primary User Score	0.25
Purpose Score	0.45
Detailed Purpose Score	0.40
Orbit Class Score	0.50
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.48**

Table 6.3: Starlink-3281 Generation V1.5 Satellite Summary

Parameter	**Assigned Value**
Name of Satellite	Starlink v2-Mini G10
Country of Operator/Owner	USA
Operator/Owner Name	SpaceX
Launch Mass (kg.)	750
Dry Mass (kg.)	700
Date of Launch	06/08/2024
Operator & Fundings	Private
Defense & Intelligence Link	**Yes**
Primary Users	Mass-Use
Purpose	Communications
Detailed Purpose	**Internet Broadband Communication/Data Relay**
Class of Orbit	LEO
Type of Orbit	Non-Polar Inclined
Operator Score	0.30
Defense-Linked Factor	+0.10
Primary User Score	0.25
Purpose Score	0.45
Detailed Purpose Score	0.40
Comments	**Starlink V2-Mini**
Orbit Class Score	0.50
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.48**

Table 6.4: Starlink Generation v2-Mini - Satellite Summary

OneWeb

The OneWeb system presents an intermediate dual-use profile, reflecting its mixed institutional–commercial governance and its growing relevance in government and security-oriented communication services. Although primarily conceived as a commercial broadband constellation, OneWeb maintains formal links with defense and governmental users, which contribute to the positive Defense-Linked factor. Its Operator score is higher than that of fully private constellations, mirroring the partnership between commercial actors and public institutions in the United Kingdom.

Parameter	**Assigned Value**
Name of Satellite	OneWeb-0354
Country of Operator/Owner	United Kingdom
Operator/Owner Name	OneWeb Satellites
Launch Mass (kg.)	148
Date of Launch	14/09/2021
Operator & Fundings	Mixed
Defense & Intelligence Link	Yes
Primary Users	Mass-Use
Purpose	Communications
Detailed Purpose	Internet Broadband Communication
Class of Orbit	LEO
Type of Orbit	Polar
Operator Score	0.50
Defense-Linked Factor	+0.10
Primary User Score	0.25
Purpose Score	0.45
Detailed Purpose Score	0.40
Orbit Class Score	0.50
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.52**

Table 6.5: OneWeb-0354 - Satellite Summary

Navigation Systems - GPS & Galileo

The comparison between GPS and Galileo shows how two systems with similar functions can occupy different positions on the dual-use spectrum due to their governance and strategic intent.
GPS is a defense-operated system with encrypted military services at its core and its institutional control by the U.S. Department of Defense strongly elevates its Dual-Use Index to a **score of 0.64**.
Galileo, instead, is governed by civilian European institutions and was explicitly designed as a non-military navigation infrastructure. Although it includes the secure PRS service for governmental users, it remains primarily a civil-security system rather than a defense asset with a **score of 0.49**.

These structural differences explain why GPS receives a significantly higher index value: the *Operator* and *Defense-Linked* dimensions capture its strategic nature, while Galileo's civil governance and open-service philosophy keep its score lower despite technical similarities.

Parameter	**Assigned Value**
Name of Satellite	Navstar GPS IIF-10 (Navstar SVN 72, PRN 8, USA 262)
Country of Operator/Owner	USA
Operator/Owner Name	Department of Defense / U.S. Air Force
Date of Launch	15/07/2015
Operator & Fundings	Defense
Defense & Intelligence Link	Yes
Primary Users	Mass-Use
Purpose	Navigation
Detailed Purpose	Global Positioning
Class of Orbit	MEO
Type of Orbit	Non-Polar Inclined
Operator Score	0.90
Defense-Linked Factor	+0.10
Primary User Score	0.25
Purpose Score	0.50
Detailed Purpose Score	0.50
Orbit Class Score	0.55
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.64**

Table 6.6: Navstar GPS IIF-10 - Satellite Summary

Parameter	**Assigned Value**
Name of Satellite	Galileo FOC FM12 (0212, Galileo 16)
Country of Operator/Owner	ESA
Operator/Owner Name	European Space Agency (ESA)
Date of Launch	17/11/2016
Operator & Fundings	Public
Defense & Intelligence Link	No
Primary Users	Mass-Use
Purpose	Navigation
Detailed Purpose	Global Positioning
Class of Orbit	MEO
Type of Orbit	Non-Polar Inclined
Operator Score	0.65
Defense-Linked Factor	- -
Primary User Score	0.25
Purpose Score	0.50
Detailed Purpose Score	0.50
Orbit Class Score	0.55
Orbit Type Score	0.55
Dual-Use-Index (Final Score)	**0.49**

Table 6.7: Galileo FOC FM12 - Satellite Summary

Yaogan Constellation

The Yaogan satellites exhibit one of the highest Dual-Use Index values in the dataset, reflecting their explicitly military nature and its role within China's defense-oriented Earth observation architecture.
Operated directly by the People's Liberation Army and equipped with a high-resolution SAR payload, the mission is designed for strategic imaging, situational awareness and intelligence acquisition. The combination of a defense operator, defense primary user and advanced radar capabilities drives all major dimensions toward the upper end of the scale, resulting in a final **score of 0.82**. This example clearly illustrates how dedicated military constellations cluster at the top of the dual-use spectrum due to their governance structure, technical configuration and operational purpose.

Parameter	**Assigned Value**
Name of Satellite	Yaogan 39
Country of Operator/Owner	China
Operator/Owner Name	People's Liberation Army (PLA)
Date of Launch	31/08/2023
Operator & Fundings	Defense
Defense & Intelligence Link	Yes
Primary Users	Defense
Purpose	Earth Observation
Detailed Purpose	Radar Imaging (SAR)
Class of Orbit	LEO
Type of Orbit	Sun-Synchronous
Operator Score	0.90
Defense-Linked Factor	+0.10
Primary User Score	0.90
Purpose Score	0.50
Detailed Purpose Score	0.70
Orbit Class Score	0.50
Orbit Type Score	0.50
Dual-Use-Index (Final Score)	**0.82**

Table 6.8: Yaogan 39 - Satellite Summary

Chapter 7

Analysis of trends

This chapter presents the results derived from dataset developed for this thesis. Each section examines how the final scores distribute across the key analytical dimensions of the model: time, orbit, region, mission purpose and constellation characteristics.
By analyzing these aggregated patterns, the chapter highlights how different space actors, orbital regimes and satellite functions contribute to the overall structure of the dual-use landscape. The following pages therefore translate the numerical output of the index into observable trends, offering a comprehensive view of how dual-use potential varies across the contemporary space environment.

7.1 Dual-Use Index Evolution Over Time

The figure illustrates the predictive margins of the Dual-Use Index from 2000 to 2024, with **95% confidence intervals**.
The **early 2000s** show a fluctuating pattern, reflecting the limited and heterogeneous nature of satellite missions in that period. The broad confidence intervals confirm a relatively small and diverse sample.
Between 2005 and 2015, the trend stabilizes, with the average predicted values remaining between 0.55 and 0.60, indicating a persistent and balanced dual-use character in satellite missions. This phase corresponds to the consolidation of Earth observation and navigation programs (e.g., Copernicus, Galileo, Beidou) that integrate both civil and strategic objectives.
From 2018 onward, a sharp decline is observed, reaching a minimum around 2020. This reduction corresponds to the massive expansion of commercial constellations in Low Earth Orbit, particularly SpaceX's Starlink, which heavily influences the dataset. Because the index attributes relatively low dual-use scores to mass-use commercial systems, their exponential increase leads to a significant drop in the

overall average prediction.
The **post-2020** recovery visible in the curve can be attributed to the new generations of Starlink satellites, which exhibit a higher dual-use potential due to improved communication capabilities and closer integration with governmental and defense frameworks, as well as to the introduction of Starshield, SpaceX's dedicated defense-oriented variant.

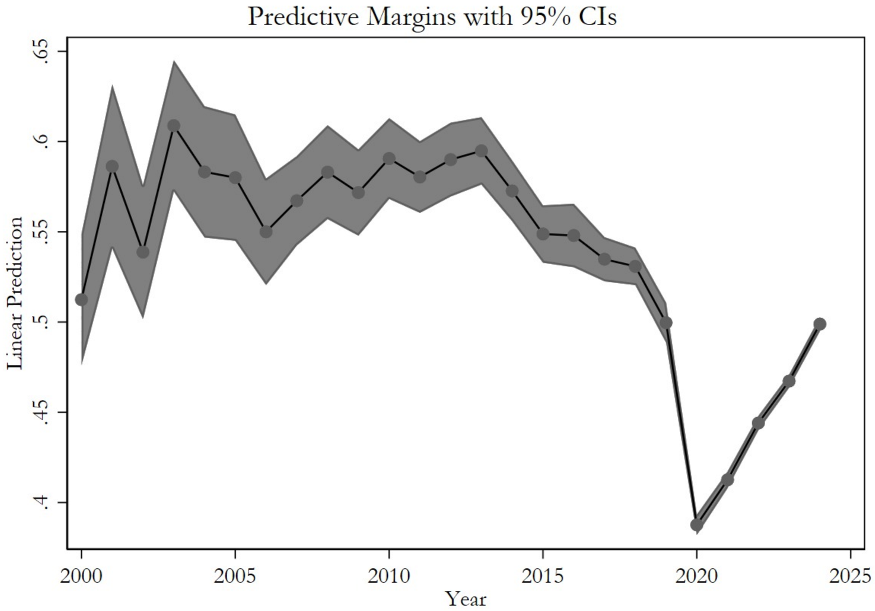

Figure 7.1: Trend 2000-2024

The **thickness of the gray bands** surrounding each line represents the 95% confidence intervals of the values. These intervals indicate the **degree of statistical certainty of the model's estimates**.
A narrower band means that the model's prediction is more reliable, with lower variability among the data points, whereas a wider band reflects greater uncertainty, often due to fewer available observations or higher heterogeneity.
Thus, the narrow confidence intervals in the most recent years reflect the larger sample size and greater homogeneity of missions (dominated by Starlink and similar systems).
This increased density of data reduces the statistical uncertainty of the model but also indicates that the recent trend is strongly driven by a single operator's orbital strategy, rather than by a balanced distribution of mission types.

7.2 Dual-Use Index Evolution by Region

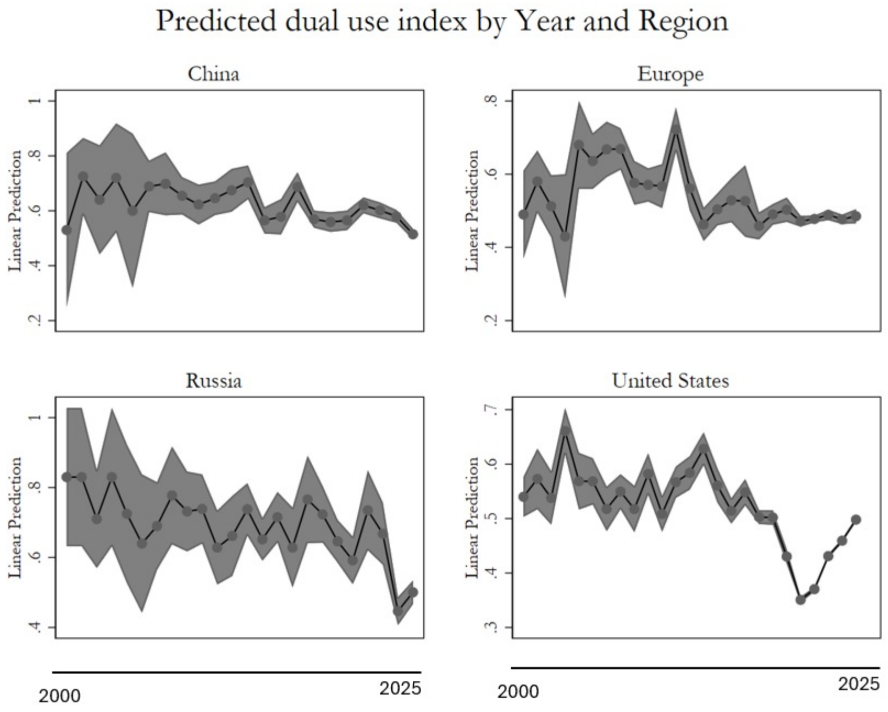

Figure 7.2: Dual Use Index By Region & Year

This figure displays the evolution of the predicted dual-use index for the major space powers which are grouped in the macro regions of China, Europe, Russia and the United States, from 2000 to 2024, including 95% confidence intervals.
Overall, the results reveal distinct regional patterns, shaped by different industrial structures and degrees of civil–military integration, but at the same time all characterized by the commercialization.

China

China shows consistently high values of the dual-use index, fluctuating between 0.6 and 0.9, with wide confidence intervals in the early years that progressively narrow after 2010. This pattern reflects the strong institutional and defense-driven organization of the Chinese space sector, where most satellite missions are directly or indirectly controlled by governmental or military entities (e.g. CNSA and PLA Strategic Support Force).
The stability in later years suggests the consolidation of state-led dual-use programs, combining Earth observation (Gaofen), navigation (Beidou) and reconnaissance (Yaogan) capabilities within a unified framework.

Europe

Europe shows moderate and stable dual-use values, generally between 0.5 and 0.6. This reflects the balanced nature of the European space sector, where large institutional programs (ESA and national agencies) coexist with an expanding group of commercial companies.
Civil missions like Copernicus and Galileo form a stable core, while national projects and private operators add additional capabilities, including several dual-use Earth-observation systems. This mix creates a portfolio that is not mainly military and not fully commercial either, but naturally hybrid.
The narrower confidence intervals in recent years suggest that Europe's satellite activity has become more consistent.

Russia

Russia exhibits the highest dual-use values and the greatest variability in the early 2000s, reflecting a satellite fleet still dominated by military systems.
After 2010, the curve shows a progressive and steady decrease. This evolution does not indicate a reduction in military capability, but rather a structural transformation in the composition of Russia's space activities.
In the last decade, an increasing share of Russian launches has consisted of commercial and mixed-purpose missions. As a result, the overall dual-use index naturally shifts toward more balanced values, reflecting a portfolio that is no longer almost exclusively defense-oriented. At the same time, this diversification coexists with continued strategic investments, including the EKS early-warning constellation and new reconnaissance platforms, which maintain the core of Russia's military space architecture despite the growing presence of non-military missions.

United States

The United States displays intermediate and stable values (around 0.5–0.6) until 2018, followed by a sharp decrease near 2020.
This pattern is mainly driven by the massive expansion of the Starlink constellation, which dominates the sample and pulls the average toward more civil-oriented values. However, the post-2020 recovery is associated with the deployment of new-generation Starlink satellites with higher dual-use potential and the parallel introduction of Starshield, SpaceX's defense-focused system.
The narrow confidence intervals after 2020 confirm that the large number of commercial satellites strongly defines the statistical behavior of the U.S. dataset.

7.3 Dual-Use Index Evolution by orbit (LEO vs GEO)

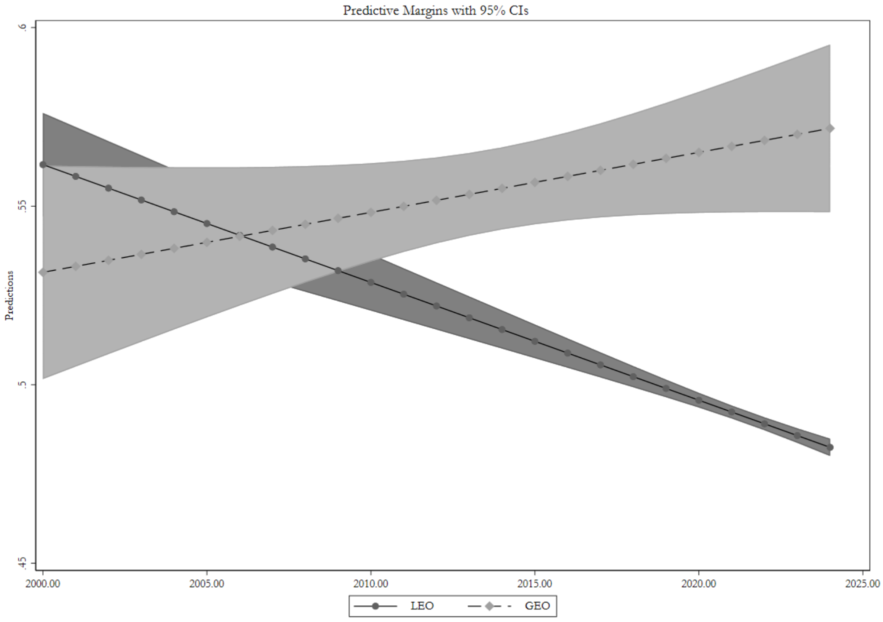

Figure 7.3: Trend LEOvsGEO

In this second graph it is described the comparison of the evolution between satellite in LEO vs satellites in GEO over the years. Two opposing trends emerge clearly:

- **LEO** shows a progressive decrease in predicted values, meaning that new missions in this orbit are becoming increasingly commercial and civilian in orientation, which can be easily explained by the proliferation of mass-use broadband systems.
- **GEO**, conversely, exhibits a slight upward trend, which suggests that missions in geostationary orbit are retaining or even reinforcing their strategic and military role.

After 2005, the two curves cross, symbolically marking a shift in the orbital balance of dual-use activities: while GEO remains associated with traditional strategic assets, LEO becomes the dominant orbit in terms of quantity but less military in nature, emphasizing the structural diversification of space activities.

Analyzing the gray areas, in the early years (2000–2010), the confidence intervals are noticeably wider, particularly for GEO satellites, indicating a limited number of data points and a higher dispersion in the observed values. From around 2015 onward, the bands narrow significantly for LEO, accordingly to what said before, showing that the growing number of satellites and the increasing uniformity of their characteristics have made the predictions more robust and consistent.
Overall, this difference in band width highlights a stronger statistical reliability for LEO trends, while GEO predictions should be interpreted with greater caution due to their broader uncertainty range.

7.4 Frequency Distribution of Dual-Use Scores

The following histograms were generated in Excel by processing the dataset to count the frequency of each occurrence of the final score, corresponding to the Dual-Use Index of the satellites. The charts display the distribution for the years 2015, 2019 and 2024, allowing the evolution of the index to be observed over time.

In **2015** (Figure 7.4), the dataset includes **131 observations**. The frequency distribution appears balanced and diversified, suggesting a heterogeneous composition of satellites with different dual-use potentials. The values are spread across multiple score intervals, indicating the coexistence of both civil-oriented and dual-purpose missions within the orbital environment.

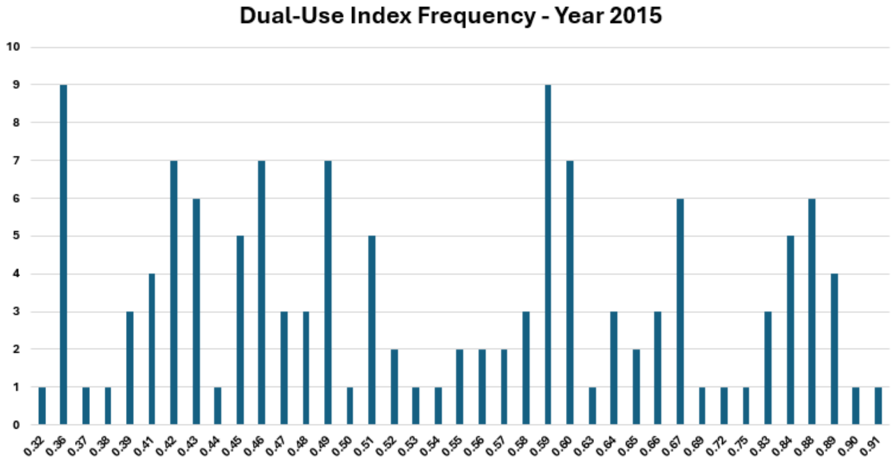

Figure 7.4: 2015 Histogram

In **2019** (Figure 7.5), the sample grows to **272 observations**, still maintaining a relatively varied distribution. However, the emergence of a clear peak begins to appear, mainly due to the first generation (V1) of Starlink satellites, marking the early stage of the constellation's expansion.

From 2019 onward, the massive deployment of Starlink systems increasingly dominates the dataset. In **2024** (Figure 7.6), with **2,181 observations**, the concentration of satellites with similar, relatively low dual-use scores produces a sharp single peak around a score of 0.48, which alone accounts for 1,569 entries, corresponding to the Starlink V2 Mini generation.
This numerical predominance compresses the rest of the distribution, flattening the diversity observed in earlier years.

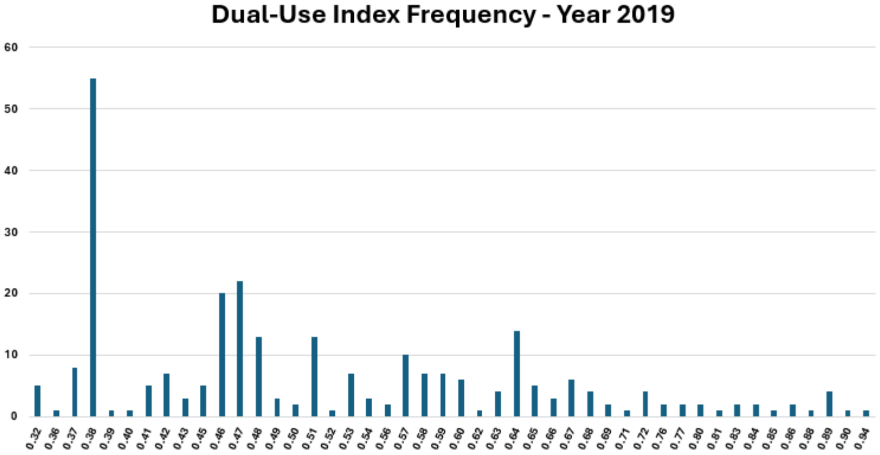

Figure 7.5: 2019 Histogram

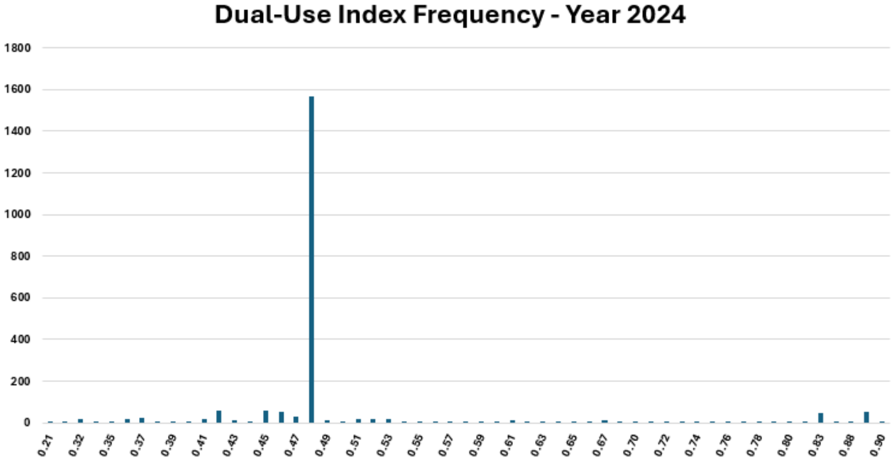

Figure 7.6: 2024 Histogram

For this reason, a second version of the 2024 histogram (Figure 7.7) was generated **excluding the Starlink constellation**, leaving **618 remaining observations**. Without Starlink, the distribution regains its variability and multiple peaks re-emerge: the higher dual-use scores (above 0.8) are primarily associated with the american Starshield and the chinese Yaogan missions, while the mid-range peak around 0.48 is populated by SISTRIOS, OneWeb and Qianfan satellites.

This filtered version provides a more representative overview of the global satellite landscape, highlighting that, beyond the commercial mega-constellations, dual-use dynamics remain active and diversified across different orbital regimes and operators.

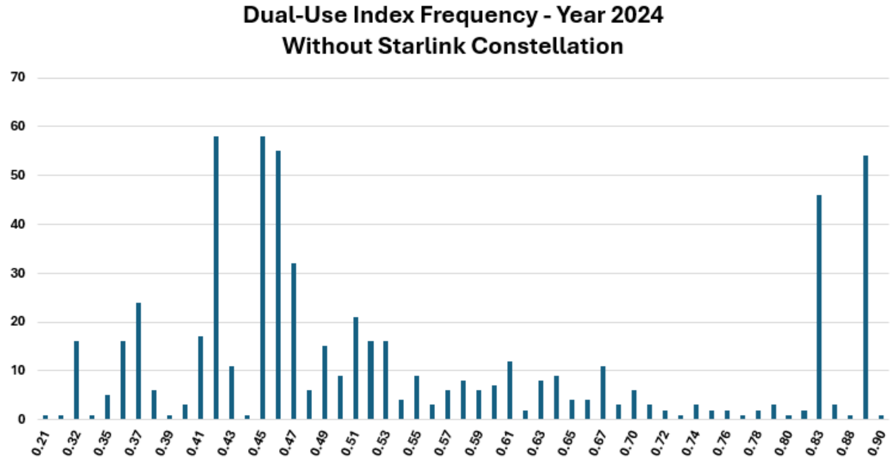

Figure 7.7: 2024 Without Starlink Histogram

Chapter 8

Conclusions And Limitations

This thesis set out to explore the increasingly blurred boundary between civil and military space activities by developing a quantitative model capable of measuring the dual-use potential of satellite systems. The work began with the observation that today's space domain is no longer organized around a clear separation between peaceful infrastructures and defense-oriented assets. Instead, it has evolved into a hybrid ecosystem where technology, governance and commercial innovation frequently overlap, creating complex forms of interdependence.
Within this context, the Dual-Use Index proposed in this thesis represents an attempt to move beyond traditional binary classifications and to capture the degree to which different satellites can be repurposed or employed for strategic objectives, even when originally conceived for civilian or commercial purposes.

The analysis of satellites launched between 2000 and 2024 highlights several important trends. The most evident is the growing influence of commercial actors, whose large constellations have reshaped the structure of the orbital environment. Systems such as Starlink, deployed in unprecedented numbers, have lowered the average dual-use score in the last decade, not because they lack strategic relevance, but because their primary design remains anchored to mass-use commercial services. This quantitative dominance modifies the statistical behavior of the whole dataset, demonstrating how the expansion of the New Space economy has become a central driver in the evolution of dual-use dynamics.

At the same time, the results confirm that state-led and defense-oriented programs remain essential pillars of strategic capability.
China continues to display consistently high values, reflecting its strong integration between civil and military space activities. Europe presents a more balanced profile, characterized by large institutional missions with stable dual-use characteristics, complemented by national systems such as COSMO-SkyMed. The United States

shows a hybrid pattern: the proliferation of commercial systems reduces the overall index, but the emergence of next-generation constellations with enhanced communication and defense-linked features indicates a renewed dual-use potential.
The regional comparison therefore reveals not only technical differences but also structural distinctions in the way space ecosystems are organized and governed.

A similar contrast emerges when analysing different orbital regimes. LEO has progressively become the domain of commercialization, hosting a large number of mass-use satellites with relatively low dual-use scores. Conversely, GEO maintains a clear strategic connotation, hosting communication, relay and surveillance missions with high defense relevance.
This divergence reflects the parallel development of two space economies: one commercial, distributed and driven by private investment and one institutional, smaller in scale but crucial for national security. The model successfully captures these patterns, demonstrating its ability to interpret dual-use as a continuum shaped by ownership structures, technological configurations and operational roles.

Despite these contributions, the study also presents several limitations that must be acknowledged.
The most significant concerns the availability and quality of data. Many satellites, especially those operated by military institutions or authoritarian states, lack detailed public information on payloads, communication protocols or maneuvering capabilities. As a result, some scores inevitably rely on indirect inference or partial descriptions, which may lead to underestimation or overestimation of their strategic potential.
Another limitation arises from the absence of universally accepted ground-truth labels. Since no international database classifies satellites as civil, dual-use or military, the model depends on contextual interpretation, which, remains influenced by the nature of available sources.

The semi-quantitative nature of the scoring method also introduces an element of subjectivity. Even with a structured rubric, certain parameters, particularly organizational ones such as operator type or primary user, reflect differences in institutional culture and geopolitical context.
Moreover, due to incomplete or inconsistent technical data, some variables that could have enhanced the assessment of military potential, such as mass, fuel capacity or propulsion type, could not be included.
These characteristics would have provided valuable insights into maneuverability and operational flexibility, both relevant in strategic scenarios.

Finally, it is important to underline that the database used in this thesis combines objective descriptive information taken from official sources with modeled variables resulting from the scoring system. While the former is factual, the latter is the outcome of methodological choices and should be read with this distinction in mind.
Future research could integrate additional technical parameters, refine weighting coefficients or expand the model to include ground segment infrastructure and launch providers, which increasingly play a role in dual-use architectures.

Overall, this thesis argues that dual use in space is not a marginal characteristic, but a fundamental property of the contemporary orbital environment.
The Dual-Use Index offers a structured and adaptable framework to interpret this complexity, providing a starting point for further academic, industrial and policy-oriented analyses. By quantifying the gray zone between civil and military missions, the model invites a more nuanced understanding of how technological innovation, market dynamics and geopolitical competition interact in space and how these interactions will shape the future of global space governance.

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