A Survey of International Telecommunication Union (ITU) Space Station License Applications in the Geosynchronous Orbital Regime (GEO)

Thomas G. Roberts*
Massachusetts Institute of Technology
Richard Linares†
Massachusetts Institute of Technology

ABSTRACT

The majority of active satellites in the geosynchronous (GEO) orbital regime perform consistent station-keeping maneuvers to stay near a particular geographic longitudinal position for their entire operational lifetimes, from orbital insertion to retirement. To avoid issues of congestion due to satellites operating physically near one another at similar longitudinal positions while propagating signals that are spectrally near one another at similar radio frequencies—which can increase the threat of satellite-on-satellite collisions or harmful radio-frequency interference, respectively—satellite operators must acquire space network licenses from the International Telecommunications Union (ITU), a specialized agency of the United Nations, prior to launch. Since 1971, the ITU has granted licenses to satellite operators to propagate signals at particular frequencies from particular orbital slots, or fractions of the geostationary belt measured in longitudinal degrees. Although the GEO orbital regime is indeed popular, the number of space network licenses granted by the ITU far exceeds the number of real, active satellites launched to the domain. This study compares the ITU space network license environment with the active on-orbit satellite population in GEO by using information from space network filings available in the ITU's Space Network List (SNL) and Space Network Systems (SNS) databases and orbital element data from the space object catalog maintained by the United States Space Force's (USSF) 18th Space Control Squadron (18 SpCS) and made public on Space-Track.org. An algorithm for matching GEO satellites to space network licenses is developed and applied to all space network filings received prior to December 31, 2021. The algorithm is also evaluated on all GEO satellites actively performing station-keeping maneuvers as of January 1, 2022, for which actual station-kept positions are compared to the nominal longitudinal positions prescribed in satellites' matched licenses. The paper concludes with a discussion on select results by both individual ITU member states that file space network applications and space operators that make use of them.

1. INTRODUCTION

Among other responsibilities, telecommunications regulators—including the International Telecommunications Union (ITU) at the international level and the U.S. Federal Communications Commission (FCC) at the federal level in the United States—are tasked with avoiding harmful interference in the radio-frequency spectrum between space networks stationed on satellites in orbit around the Earth. To do so, regulatory agencies accept filings from satellite operators that describe their proposed space networks' configurations (which are often submitted well in advance of the corresponding satellites' launches to orbit), de-conflict between applications that could lead to harmful interference, and issue mutually compatible licenses to operators. In an ideal world, space network licenses from telecommunications regulators ensure that satellites that operate physically near one another do not use the same radio frequencies for sending or receiving data. For space networks hosted on satellites in low-Earth orbit (LEO) and medium-Earth orbit (MEO), regulators consider proposals based on orbital characteristics that physically describe satellite constellations—the inclinations and right ascensions of the ascending node (RAANs) of the constellations' orbital planes; the semi-major axes, eccentricities, and arguments of perigee of particular orbits within those planes; and phasing angles, which describe individual satellites' positions within those orbits—and together can be used to deduce satellites' positions. In geosynchronous orbit (GEO), on the other hand, the proposed physical location of a satellite can often be distilled into a single, delightfully simple, one-dimensional figure: geographic longitude.

*Ph.D. Candidate, Department of Aeronautics and Astronautics. E-mail: thomasgr@mit.edu
†Associate Professor, Department of Aeronautics and Astronautics. E-mail: linaresr@mit.edu

Because objects in GEO appear to move relatively slowly in the sky to observers on the Earth's surface, they are particularly well-suited for reference by geographic coordinates: latitude, longitude, and altitude in the Earth-centered, Earth-fixed (ECEF) reference frame. Objects in GEO that are positioned on the geostationary belt—that is, they orbit in an equatorial, circular orbit, with geostationary altitude—stay stationary in the sky when observed from the ground. In geographic coordinates, a geostationary satellite at 0° latitude, some longitudinal position between 180°W and 180°E, and geostationary altitude. Although maintaining such a position in the geostationary belt for any extended period of time requires periodic station-keeping maneuvers—and only some GEO satellite operators choose to actually pursue such maneuvers—applicants for telecommunications licenses need only cite a single longitudinal position of their choice in GEO, known as their space network's *nominal* longitude.

This paper describes a study that uses publicly available information from one telecommunications regulator, the ITU—a specialized agency of the United Nations (UN)—to describe the current space network license environment in GEO. To offer a sense of the relationship between licenses and actual satellites that may be making use of those licenses, an effort to match space networks to on-orbit satellites using publicly available data from the United States Space Force's (USSF) 18th Space Control Squadron (18 SpCS) space object catalog hosted on Space-Track.org is developed and described.

The datasets on which this work relies are described in more detail in the following section. The method by which the developed algorithm matches ITU space network licenses with GEO satellites is described in Section 3. The relationship between the space network license environment and the GEO satellite environment, as described by the matching algorithm, is presented in Section 4 and discussed in Section 5. The final section comments on the challenges faced while developing the matching algorithm as well as opportunities for future study.

2. RELEVANT DATASETS

In this work, the term "space network" refers to the configuration of a proposed GEO space system—in terms of longitudinal position and radio frequencies—described in filings submitted by "administrations," or ITU members states, to the Union's Radiofrequency Bureau (BR). The more colloquial term "license" is used when a space network has received protected status by the ITU and a "notification of space station" filing from the corresponding administration has been received by the BR. Until protected status is granted, space network filings are referred to as "applications." Because not all administrations that receive space network licenses actually use them, there are many more space network licenses than actual GEO satellites. This section describes the relevant datasets that provide information on both space network licenses and actual GEO satellites.

Two data sources from the ITU provide information on historical space network applications and licenses. The first is a list of space networks by frequency band and orbital position formally known as "Part A of the Space Network List," but henceforth described as simply the "Space Network List" (SNL). The SNL is publicly available on the ITU's website [3]. The second is the "Space Network Systems Database," henceforth described as the "Space Network System" (SNS). The SNS is also available on the ITU's website, but is restricted to users with annual subscriptions or who are members of the Union's Telecommunication Information Exchange Service (TIES) [4].

Data describing the launch information, longitudinal positions, and operational status of GEO satellites is provided by USSF, the European Space Agency (ESA), and launch datasets managed by Jonathan McDowell, an independent satellite population analyst. The space object catalog maintained by USSF's 18 SpCS provides GEO satellites' launch dates, corresponding spaceports, and historical orbital elements, from which longitudinal positions can be derived. ESA's annual "Classification of Geosynchronous Objects" reports provide some information on the status of GEO satellites, including whether they are pursuing the station-keeping maneuvers required to maintain a longitudinal position in the geostationary belt. Launch vehicle records maintained by satellite population analyst Jonathan McDowell provide launch vehicle family information for GEO satellites.

2.1 Space Network List

The SNL contains information about space networks throughout the ITU's lengthy filing process, including sections associated with advanced publication information (denoted with the letter "A"), coordination requests (denoted with the letter "C"), notifications of space stations (denoted with the letter "N"), and due diligence data submitted by the applicant administration (denoted with the letter "U") [7]. The first and second sections are associated with space network applications—and thus do not yet enjoy international recognition and protection from interference by other space networks—while the third and fourth are associated with licensed space networks. These one-letter abbreviations refer to space networks applying to either "non-planned" or "planned" services. "Non-planned" services are those that use frequency bands that have been made available by the ITU on a first-come, first-served basis [1]. Just three countries—the United States, Russia, and China—hold about half of all non-planned space network licenses. "Planned" services are those that use frequency bands that have been distributed by the ITU amongst applicant administrations on a more equitable basis—a concept developed over two meetings of the "World Administrative Radio Conference on the Use of Geostationary-Satellite Orbit and the Planning of Space Services Utilizing It" in 1985 and 1988—to ensure future access to the geostationary belt by developing nations that operate few or no satellites at the time of application [1]. Table 1 describes the number of filings in each section of the SNL for both non-planned and planned services received by the BR before December 31, 2021.

ITU Notification Reason	Abbreviation	Non-planned Services	Planned Services
Advance Public Information	A	70	–
Coordination Request	C	1852	–
Notification of Space Station	N	1392	142
Due Diligence	U	1533	94

Table 1: The number of space network filings in each of the four sections of ITU's Space Network List for both non-planned and planned services. Space network filings with the "A" and "C" abbreviations have not yet received protected status. Filings with the "N" abbreviation correspond to networks that have been granted protected status, while those with the "U" abbreviations, filed later, include more information about the planned use of a particular licensed satellite network [3].

To illustrate the distribution of space network licenses across the geostationary belt by longitude, the filings in the SNL should be filtered to include just those that have received protected status from the ITU across both non-planned and planned services, otherwise many space networks will be double-, triple, or quadruple-counted depending on their progress within the ITU's licensure process. Figure 1 plots the longitudinal distribution of space network filings for which notification of protected status has been received (that is, those with an ITU abbreviation of "N" in the SNL) for non-planned and planned services in comparison to the longitudinal distribution of all GEO satellites pursuing station-keeping maneuvers as of January 1, 2022. The process to identify these active GEO satellites and their longitudinal positions is described in Subsection 2.3.

As of September 5, 2022, there were 1392 and 142 space network licenses filed before December 31, 2021, for non-planned and planned services, respectively, but only 506 actively station-keeping satellites as of January 1, 2022.

The distribution of both ITU space network licenses and actively station-keeping GEO satellites across longitudes is not uniform, as some regions of the geostationary belt are more desirable to operators than others. For example, there are fewer satellites pursuing station-keeping maneuvers over the middle of the Pacific Ocean than there are over Europe. In most slots—often defined in 0.1-degree increments by the ITU but shown in 5-degree increments in Figure 1 for clarity—the number of ITU licenses greatly exceeds the number of active GEO satellites.

2.2 Space Network System

The SNS offers more detailed information included in space network filings than the SNL to TIES-registered users, including those representing ITU member states and academic institutions, among other organizations [5]. Most critically for this study, the SNS includes more details from due diligence filings (those denoted with a "U" abbreviation in the SNL) submitted by administrations after their space networks have been granted licenses. Due diligence filings in the SNS include administrations' plans for deploying the satellite that will host the licensed space network. These plans are summarized in each due diligence filing's corresponding Transaction Summary (TSUM), including the manufacturer that will be contracted to produce the host satellite, a window for when it is expected to launch, and the spaceport and launch vehicle that is planned to support it. Notably, space network due diligence filings

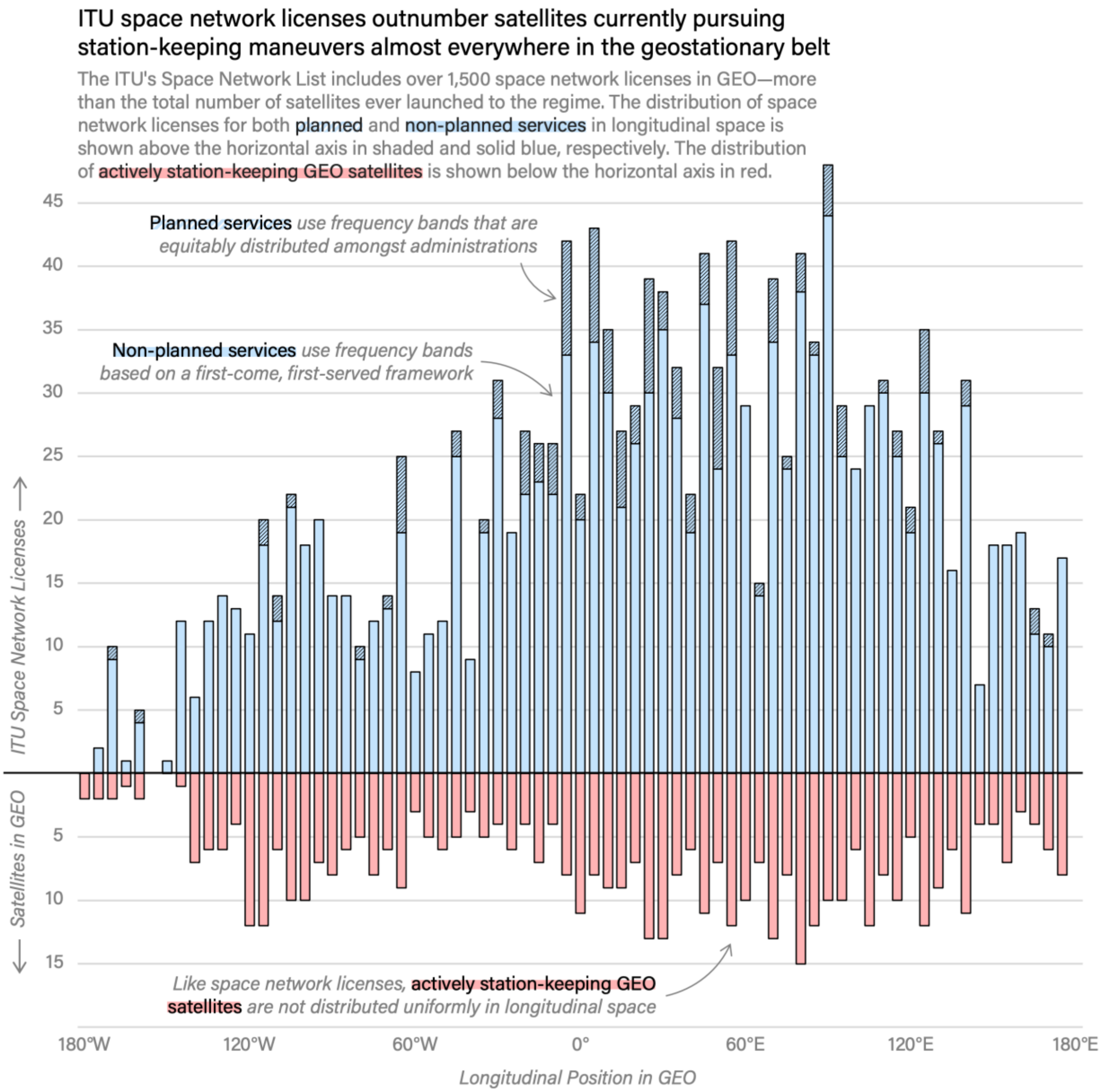

Fig. 1: Space network licenses filed by the ITU for non-planned and planned services (shown above the horizontal axis in solid and shaded blue, respectively) compared to actively station-keeping GEO satellites (shown below the horizontal axis in red) by longitude. Only licenses filed before December 31, 2021, are displayed. The distribution of actively station-keeping GEO satellites reflects their longitudinal positions on January 1, 2022.

do not include the name of the satellite that will host the space network. Instead, the filing shares the same name as those submitted earlier by the administration for the corresponding network.

Of the 1534 space network licenses plotted in Figure 1, 1278 of them also have due diligence filings. In some cases, due diligence filings were received by the BR after the satellite that hosts the licensed space network was already launched. In the future, it is likely that more than 1278 of the 1534 space networks shown in Figure 1 will have corresponding due diligence filings in the SNL and SNS as more filings are received, processed, and published by the BR.

2.3 Defining GEO satellites

In order for space network licenses to be matched with satellites actually launched to GEO, a population of GEO satellites and their corresponding launch characteristics must be generated. For this study, GEO satellites are defined as objects labeled as “Payloads” in the 18 SpCS space object catalog with at least one set of orbital elements in their historical records that places them in residence in the GEO region as defined by the Inter-Agency Space Debris Coordination Committee (IADC) between January 1, 2010, and December 31, 2021. By this definition, there are 916 GEO satellites in the 18 SpCS’s space object catalog. In this study, this group will henceforth be called simply “GEO satellites.”

Not all these GEO satellites, however, are actively pursuing the station-keeping maneuvers required to keep them near one particular longitudinal position in the geostationary belt. To filter the 916 GEO satellites down to those that are pursuing such maneuvers—a subset that will be henceforth referred to as “actively station-keeping” GEO satellites—consider the framework provided by ESA’s annual “Classification of Geosynchronous Objects” report series [2]. Each year, ESA’s European Space Operations Centre classifies GEO objects by their operational status using classes that are associated with various types of controlled and uncontrolled behavior, as deduced via historical orbital elements from a variety of sources. Controlled behavior consists of longitudinal control (under which satellites practice station-keeping in on the east-west direction) or both longitudinal and inclination control (under which satellites practice both east-west and north-south station-keeping). The 2019 edition of the report classified 498 GEO satellites as controlled [9].

Space objects can be sorted into ESA’s classes algorithmically or by inspection of satellite’s historical longitudinal positions. Longitudinal positions can be derived from orbital element data using the PyEphem Python Library [8, 9]. To verify the GEO satellite classes published in the 2019 edition of the ESA report and expand the classification scheme to objects launched after that report’s publication, but before the end of the study period on December 31, 2021, longitudinal time histories were created and inspected for each of the 916 GEO satellites identified as part of this study. GEO satellites that practice longitudinal control can be easily identified by subject-matter experts due to their characteristic maintenance of one or more longitudinal positions during their operational lifetimes. Of the 916 GEO satellites in this study, 506 were actively pursuing station-keeping maneuvers as of January 1, 2022.

Since the 18 SpCS space object catalog does not include the vehicle used to launch each object, it must be supplemented with data from another source. Launch vehicle family data for the 916 GEO satellites analyzed as part of this study is provided by Jonathan McDowell’s “General Catalog of Artificial Space Objects” and “Launch Vehicle List” [6].

3. METHODOLOGY

Because space networks rarely share a name with the satellites that host them, matching space network licenses to actual GEO satellites is non-trivial. Previous efforts to do so—including a notable, perennial series of studies by the late Luboš Perek, former director of the UN’s Office for Outer Space Affairs—rely on an assumption that the nominal longitudes prescribed in space network licenses are accurate [11]. Under Perek’s formulation, a Japanese GEO satellite that maintains a position at 138.3°E in the geostationary belt, for example, may be a good match for a space network license held by Japan at a nominal longitude of 138.2°E. When that satellite’s launch characteristics are inspected, however, it may very poorly resemble the details included in the Japanese space network’s due diligence filing, which may show that the space network was instead supposed to be launched on a satellite in another decade, with a different launch vehicle, from a spaceport on the other side of the globe. A relatively new pattern in which GEO satellites perform increasingly frequent longitudinal-shift maneuvers—where GEO satellites change the longitudinal position at which they perform station-keeping maneuvers—further challenges Perek’s assumption [9].

In an effort to interrogate the accuracy of data provided in space network due diligence filings, an algorithm was developed that queries the list of GEO satellites—including those that are not actively station-keeping—and identifies satellites with operator and launch characteristics that are similar to those prescribed in space networks’ due diligence filings.

The algorithm first scans the SNS database for sets of launch plans encoded in each space networks' TSUMs—including the date the filing was received by the BR, the planned launch window's start date, the planned launch window's end date, the planned launch site, and the planned launch vehicle—and logs them. When more than one TSUM is included in a particular space network's due diligence filing, the launch plans described in each TSUM are individually logged and tagged with that filing's name. For each set of launch plans, the GEO satellite population is queried to find the ten GEO satellites with launch dates closest to the center of the filing's planned launch window. When the filing includes only one bound on the launch window, that single bound is considered its center. When no launch window bounds are included in the network filing—which is often the case for due diligence filings that were received by the BR after the host satellite was launched—the BR filing date is considered the center of the launch window. The GEO satellites in this ten-satellite shortlist with launch dates nearest to the center of a particular space network filing's launch window—which may or may not fall *within* the corresponding filing's launch window—are then inspected for further matches with the launch plans included in the space network's due diligence filing.

Since the 18 SpCS space object catalog allows countries, groups of countries, and non-state organizations to be listed as satellite operators while the ITU considers only ITU member states as space network administrations, a cross-reference scheme must be established to match satellite operators to space network administrators. GEO satellite operators are considered a match with a space network filing's administration if the administration's ITU country symbol appears alongside the operator's 18 SpCS abbreviation in Table A2.1. The launch vehicles described in space networks' due diligence filings can range from being rather broad (such as "U.S. Government Launch Vehicle") to quite narrow (such as "Delta II-7925.8," a specific variant from the Thor launch vehicle family). To match GEO satellite's launch vehicle families to space network filings' planned launch vehicles, the launch vehicles described in space networks' due diligence filings must be manually associated with one or more of the launch vehicle families from Jonathan McDowell's "List of Launch Vehicles." GEO satellite launch vehicle families are considered a match to space network filings' planned launch vehicles when they appear in the same row of Table A2.2. Matching GEO satellites' origin spaceports to planned launch sites in space networks' fillings is more trivial, since spaceport abbreviations can be easily deduced from planned launch site names, as shown in Table A2.3.

Of the ten GEO satellites for which launch characteristics were evaluated for matches, the five with the most matches—including those between GEO satellite operators and ITU administrators, actual launch vehicle families and planned launch vehicles, and actual spaceports and planned launch sites—are identified. If two GEO satellites both yield the same number of matches, the one with an actual launch date closer to the center of the planned launch window is ranked higher.

In most cases, the launch characteristics of a majority of the five GEO satellites identified do not closely resemble those described in a space networks' due diligence filings, but instead represent only partial matches: perhaps the satellite launched a few days or weeks after the end of the planned launch window, or it used a launch vehicle from another family as opposed to the one described in the corresponding space network's filing. To describe the spectrum of matches between GEO satellites and space network filings, the algorithm identifies the names of the satellites from the five candidates that are a full match (that is, the launch dates falls within the planned launch window, the spaceport matches the planned launch site, and the launch vehicle family that was used to support the launch matches that of the planned launch vehicle), those that are missing one component of the launch plan (date, spaceport, or vehicle), and those that are missing two components. These three match categories are henceforth referred to as "full match," "one-off partial match," and "two-off partial match." The term "partial match" refers to both one-off and two-off partial matches. For all three types of matches, the satellite's operator must match the ITU administration, under the framework described in Table A2.1.

The next section describes the results of the algorithm when evaluated on all space network licenses from the ITU's SNL and all GEO satellites identified in Section 2.3.

4. RESULTS

Of the 1278 space network licenses with due diligence filings sent to the BR, the algorithm described in the previous section could identify full matches with actual GEO satellites for 677 of them. Including one-off partial matches increases that total to 932 licenses; including two-off partial matches further increases that number to 985, or 77

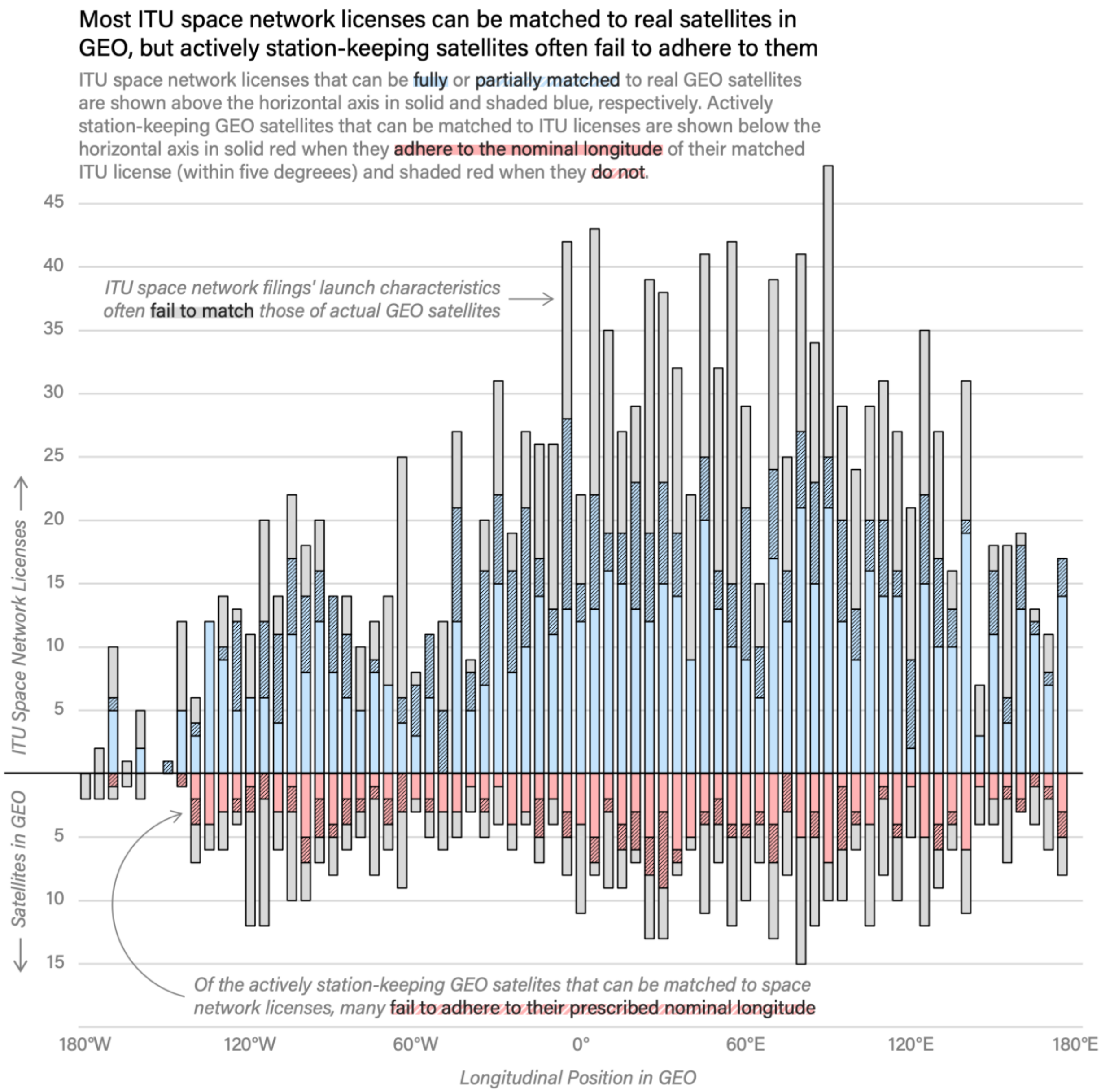

Fig. 2: Space network licenses matches with GEO satellites (shown above the horizontal axis) and actively station-keeping GEO satellites with space network licenses (shown below the horizontal axis) by longitude. Above the horizontal axis, space network licenses that could be fully and partially matched with GEO satellites are shown in solid and shaded blue, respectively. Both the space networks with due diligence filings that could not be matched to GEO satellites and those with no due diligence filings at all are shown in gray. Below the horizontal axis, actively station-keeping satellites that adhere to the nominal longitude described in their matched space network license (within five degrees) are shown in solid red. Those that fail to adhere to the nominal longitudinal position (that is, the offset angle is greater than five degrees) prescribed in their space network license are shown in shaded red. The actively station-keeping satellites for which the algorithm found no space network license match are shown in gray.

percent of all licenses with due diligence filings. Because the algorithm allows for double-matching—in which two or more space network licenses are matched with the same GEO satellite—not all actively station-keeping GEO satellites are matched with licenses, despite there being more matches than actively station-keeping GEO satellites. Of the 506 actively station-keeping satellites in GEO, 330 could be algorithmically matched with ITU space network licenses either in full or in part. Of those that could be matched with licenses, 123 were station-keeping within 0.1

degrees of the nominal longitude prescribed in their matched license on January 1, 2022; 164 were station-keeping within 1 degree, and 176 within 5 degrees.

Figure 2 describes the distribution of these matching results in longitudinal space. Above the horizontal axis, the space network filings that could not be matched to GEO satellites, shown in gray, include both those for which no due diligence filings have been completed (as was the case for 256 of the 1534 licenses) and those for which the algorithm could not find a full or partial match within the GEO satellite population. Table A1.1 describes the same results described in Figure 1, but by satellite operator.

5. DISCUSSION

The results presented in the previous section paint a clear picture: many of the space network licenses granted by the ITU poorly describe the satellites that host them and many GEO satellites do not appear to adhere to the nominal longitudinal positions prescribed in their licenses.

If launch characteristics represented in space networks' due diligence filings were perfectly accurate—a claim not made by the ITU—then all space network licenses for which there are no full matches found by the algorithm described in Section 3 could be considered "paper satellites," a phrase that refers to space networks not yet hosted on real satellites. A more likely reality is twofold: satellite launch plans change over time and filings are not always updated to reflect those changes; and satellites are hosting more than one space network, including ones that may have originally been planned for other satellites with other launch characteristics. The results presented in Figure 2 and Table A1.1 show that the number of space network licenses that can be matched to GEO satellites and the number of actively station-keeping GEO satellites that themselves can be matched to space network licenses vary little by longitude, but more noticeably by operator.

Of all the countries that operate a satellite in GEO, just four actively station-keep the same number of satellites as the number of ITU space network licenses they hold—Algeria, Belarus, Bolivia, and Nigeria—each with one GEO satellite and one ITU space network license. Matches between space network licenses and GEO satellites could be identified for three of these four countries—Algeria, Bolivia, and Nigeria—which showed that each operator adheres to the nominal longitude prescribed in their space network license by station-keeping at positions 0.02 degrees or closer. The situation for countries that hold many more ITU space networks licenses and operate many more actively station-keeping satellites is more complicated.

The United States holds more ITU space network licenses than any other administration (24.1 percent of those published in the SNL) and actively station-keeps more GEO satellites than any other country (23.1 percent of the total population). Yet of the 117 actively station-keeping U.S. satellites, only 43 could be fully or partially matched with an ITU space network license. Worse yet, of those 43 matched satellites, most do not station-keep at the longitudinal position prescribed in the corresponding space network license. Instead, the average offset—or angular distance between nominal and actual longitudinal positions is over 50 degrees for U.S. satellites. Russia—the administration that holds that second-highest number of ITU space network licenses at 12.5 percent of those published on the SNL—has a slightly smaller average offset at about 40 degrees, but operates a smaller number of satellites (5.9 percent of the total population). Of the three administrations that together hold nearly half of all of the ITU space network licenses for non-planned services—the U.S., Russia, and China—the ratio of actively station-kept GEO satellites to ITU space network licenses is highest for China, which actively station-keeps 14 percent of the GEO satellite population, but holds just under 10 percent of all space network licenses. Although France—which follows China in terms of the number of ITU space network licenses held, as shown in Table A1.1—holds just about as many licenses as China, it only operates three satellites in GEO. Of those three, just one could be matched using the matching algorithm described in Section 3: *Athena-Fidus* (Satellite #: 39509), the French-Italian joint-operated satellite that inspired the French secretary of the armed forces to criticize Russia for operating its *Luch (Olymp)* satellite (Satellite #: 40258) at a longitudinal position France found to be too close to *Athena-Fidus* in 2018 [10].The French-Italian satellite's offset was small compared to its matched space network license: less than 0.2 degrees. *Luch*, on the other hand, could not be matched to any ITU space network license in the SNL, despite pursuing almost 30 longitudinal-shift maneuvers so far in its operational lifetime [9].

France's relatively low number of actively station-kept satellites in comparison to its relatively high number of ITU space network licenses is likely due to the country serving as an ITU administrator for commercial satellite operators based in Europe, such as the European Telecommunications Satellite Organization (Eutelsat), the European Organization for the Exploitation of Meteorological Satellites (Eumetsat), or ESA. Non-state operators actively station-keep a sizeable portion of the GEO satellite population—about 27 percent—but cannot hold ITU space network licenses. Instead, these organizations must submit filings with an ITU member state acting as the corresponding administration. Nonetheless, non-state operators can be matched to space network licenses held by a shortlist of administrations via cross-references described in Table A2.1 and evaluated for adherence to their nominal longitudes. Of the nine non-state operators with actively station-keeping satellites, the operator with the highest average offset is Eumetsat at over 116 degrees. The operators with the lowest average offsets are ESA and Eutelsat at approximately 0.1 and 0.6 degrees, respectively.

Near the end of the Table A1.1, observant readers may notice that there are some countries—Azerbaijan, Bangladesh, Taiwan, and Turkmenistan—that curiously appear to actively station-keep one or more GEO satellites despite not holding a single ITU space network license. Although these operators may simply be operating satellites outside of the ITU's regulatory framework, other explanations may be more likely. In some cases, these countries jointly operate their GEO satellite with another country, which may hold the relevant ITU space network license. In other cases, the countries may autonomously operate satellites on behalf of a consortium of organizations, in which another country is serving as the corresponding space network's ITU administration

6. CONCLUSIONS

Until GEO satellite operators improve the accuracy and promptness of the due diligence filings associated with their ITU space network licenses or the ITU's BR begins to offer more information on whether their published space networks have been brought into service, the matching algorithm developed as part of this study will continue to fail to find matches between all GEO satellites and licenses on the ITU's SNL. Without comprehensive matching, both the prevalence of paper satellites and the adherence to nominal longitudinal positions amongst satellite operators cannot be realized.

To improve the completeness of the matching algorithm, future iterations of this study should rely on shortlists of ITU member states through which each non-state GEO satellite operator pursues ITU space network licenses that are verified by the non-state operators themselves. In addition, this study would benefit from the subject-matter expertise of ITU BR representatives, who could share their experience receiving flings from administrators and shed light on the culture of administrations issuing revisions to their filings, the cadence with which the SNL is updated, and the process by which two or more space network licenses with different nominal longitudinal positions may be hosted on the same GEO satellite. Currently, the matching algorithm weighs the launch date, launch site, and launch vehicle fields of space networks' due diligence filings equally as it queries the GEO satellite population for matches, with no regard to the possibility that any of those fields may be more likely than others to be realized by host satellites. In addition to ITU BR representatives, space operator professionals with experience applying for space network licenses from telecommunications regulatory agencies could offer suggestions to changes to the launch characteristics weighting scheme currently used by the matching algorithm.

This work inspires many opportunities for future study. With no changes to the matching algorithm, the prevalence of duplicate matches between space networks and GEO satellites—in which one GEO satellite is matched with more than one ITU space network—should be studied in greater detail. In cases of duplicative matches with a GEO satellite that has perpetually pursued station-keeping maneuvers at an individual longitudinal position, how does the filing date of the most correct space network license—the one with the smallest offset angle—compare with the filing dates of the other matched licenses? How often do satellite operators revise their space network licenses to change the nominal longitudinal position versus abandoning the license in one of the application steps described in Table 1? Perhaps the most interesting opportunities for future work include studying compliance with ITU slotting guidelines in more detail on an operator-by-operator basis. Of the satellites that pursue the most longitudinal-shift maneuvers, how many hold licenses at each of the various longitudinal positions at which they station-keep? Across the GEO satellite population, what fractions of operational lifetimes are spent in compliance with ITU slotting guidelines?

The ITU's distribution of space network licenses in GEO is the only example of an implemented international slotting framework in space. As other orbital regimes—in which satellite operators must use many different orbital parameters to describe their applicant constellations' configurations—become more congested and slotting mechanisms are proposed for them, it is critical to interrogate the successes and failures of the ITU's slotting framework in GEO. LEO slotting framework designers should not assume perfect or near-perfect compliance to ITU slotting guidelines amongst GEO satellite operators as they propose new systems for the future. As regulatory agencies begin to adopt new policies for issuing telecommunications licenses for LEO, they must consider how the rules in GEO are both followed and ignored by operators.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1745302.

REFERENCES

[1] A. L. Allison. *The ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century*, Springer International Publishing, 2014.
[2] European Space Operations Centre. "Classification of Geosynchronous Objects," Issues 12 to 21, 2010 to 2019.
[3] International Telecommunications Union. "Space Network List (SNL)," accessed September 5, 2022, https://www.itu.int/en/ITU-R/space/snl/Pages/default.aspx.
[4] International Telecommunications Union. "Space Network System Online," accessed September 5, 2022, https://www.itu.int/sns/.
[5] International Telecommunications Union. "TIES Services," accessed September 5, 2022, https://www.itu.int/en/ties-services/Pages/default.aspx.
[6] J. C. McDowell. "GCAT: General Catalog of Artificial Space Objects," accessed September 5, 2022, https://www.planet4589.org/space/gcat/web/launch/index.html.
[7] X. Laurenson. "Space Services Website: SNL and SNS Online," *World Radiocommunication Seminar 2012* (December 3-7, 2012), Geneva, Switzerland.
[8] B. C. Rhodes. "PyEphem: Astronomical ephemeris for python," Astrophysics Source Code Library, 2011.
[9] T. G. Roberts and R. Linares. "A Survey of Longitudinal-Shift Maneuvers Performed by Geosynchronous Satellites from 2010 to 2021," IAC-22.C1.IP.9.x68421, *73rd International Astronautical Congress*, Paris, France (September 18-22, 2022).
[10] T. G. Roberts. "Luch (Olymp) / Athena-Fidus," Satellite Dashboard, December 14, 2020, https://satellitedashboard.org/analysis/luch-olymp-athena-fidus.
[11] C. Ron and M. Machoň. "Towards Sustainable Use of the Geostationary Orbit," August 19, 2022, https://geostationary.cz/Perek_follow-up_rev_2.html.
[12] Secure World Foundation, Center for Strategic and International Studies, and the University of Texas at Austin's Department of Aerospace Engineering and Engineering Mechanics. "Satellite Dashboard," 2022, https://satellitedashboard.org/.

APPENDICES

A1. Extended Results

Table A1.1 describes the results of the matching algorithm described in Section 3 on an operator-by-operator basis. The "NP" and "P" columns in the table refer to non-planned and planned services, respectively. The "Partial Match" column refers to both one-off and two-off partial matches. The "No DD Filing" column refers to the number of space network licenses in the SNL by country for which no due diligence filing has been received by the BR. The several columns with "offset" in their name refer to the angular separation between actual satellite positions and nominal longitudes in the geostationary belt.

Country or Organization	Space Network Licenses			Space Network / GEO Satellite Match Results				Actively Station-keeping GEO Satellites				
	Total % All	NP	P	Full Match	Partial Match	No Match	No DD Filing	Total % All	No Match	>5° Offset	≤5° Offset	Avg. Offset
United States	**370** 24.1%	368	2	171	111	86	2	**117** 23.1%	74	30	13	51.92°
Russian Federation	**192** 12.5%	167	25	81	36	50	25	**30** 5.9%	10	11	9	40.30°
China	**148** 9.6%	140	8	71	33	36	8	**71** 14.0%	40	11	20	13.10°
France	**145** 9.5%	114	31	81	19	14	31	**3** 0.6%	2	0	1	0.18°
United Kingdom	**76** 5.0%	73	3	41	23	9	3	**10** 2.0%	4	4	2	45.67°
Japan	**74** 4.8%	74	0	46	16	12	0	**20** 4.0%	10	0	10	0.31°
India	**63** 4.1%	54	9	30	5	19	9	**24** 4.7%	10	3	11	6.67°
Netherlands	**39** 2.5%	36	3	15	14	7	3	**0** 0.0%	0	0	0	–
Luxembourg	**37** 2.4%	28	9	18	7	3	9	**0** 0.0%	0	0	0	–
Brazil	**34** 2.2%	31	3	9	3	19	3	**7** 1.4%	3	1	3	8.02°
Canada	**30** 2.0%	27	3	5	13	9	3	**15** 3.0%	9	2	4	7.97°
Australia	**25** 1.6%	25	0	6	1	18	0	**7** 1.4%	4	0	3	1.60°
Papua New Guinea	**23** 1.5%	22	1	0	0	22	1	**0** 0.0%	0	0	0	–
Turkey	**23** 1.5%	21	2	8	0	13	2	**4** 0.8%	2	0	2	0.04°
Saudi Arabia	**21** 1.4%	17	4	10	3	4	4	**0** 0.0%	0	0	0	–
Indonesia	**21** 1.4%	21	0	12	3	6	0	**4** 0.8%	2	0	2	0.01°
Spain	**19** 1.2%	16	3	11	1	4	3	**9** 1.8%	5	1	3	28.28°
United Arab Emirates	**18** 1.2%	16	2	6	4	6	2	**5** 1.0%	2	0	3	0.09°
Germany	**15** 1.0%	15	0	1	1	13	0	**2** 0.4%	2	0	0	–
Rep. of Korea	**13** 0.8%	13	0	6	0	7	0	**9** 1.8%	7	1	1	39.83°
Norway	**13** 0.8%	10	3	5	3	2	3	**3** 0.6%	3	0	0	–
Thailand	**13** 0.8%	13	0	4	1	8	0	**3** 0.6%	3	0	0	–
Israel	**11** 0.7%	8	3	3	2	3	3	**3** 0.6%	0	0	3	1.13°
Malaysia	**11** 0.7%	10	1	4	0	6	1	**2** 0.4%	0	0	2	0.01°
Sweden	**11** 0.7%	6	5	1	2	3	5	**0** 0.0%	0	0	0	–
Mexico	**10** 0.7%	9	1	4	1	4	1	**4** 0.8%	4	0	0	–
Cyprus	**8** 0.5%	5	3	0	0	5	3	**0** 0.0%	0	0	0	–
Tonga	**7** 0.5%	7	0	0	0	7	0	**0** 0.0%	0	0	0	–
Vietnam	**6** 0.4%	5	1	1	3	1	1	**2** 0.4%	0	0	2	0.06°
Kazakhstan	**5** 0.3%	4	1	0	0	4	1	**2** 0.4%	2	0	0	–
Qatar	**5** 0.3%	3	2	0	0	3	2	**0** 0.0%	0	0	0	–
Egypt	**4** 0.3%	4	0	2	0	2	0	**2** 0.4%	1	0	1	0.01°
Italy	**4** 0.3%	4	0	0	1	3	0	**1** 0.2%	0	0	1	0.18°
Monaco	**4** 0.3%	0	4	0	0	0	4	**1** 0.2%	1	0	0	–

(continued)

Pakistan	**4** 0.3%	4	0	1	0	3	0	**1** 0.2%	0	0	1	0.03°
Argentina	**3** 0.2%	3	0	1	0	2	0	**2** 0.4%	1	0	1	0.20°
Bulgaria	**3** 0.2%	2	1	1	0	1	1	**1** 0.2%	0	0	1	0.01°
Côte d'Ivoire	**3** 0.2%	1	2	0	0	1	2	**0** 0.0%	0	0	0	–
Greece	**3** 0.2%	2	1	1	0	1	1	**2** 0.4%	1	0	1	0.01°
Hungary	**3** 0.2%	0	3	0	0	0	3	**0** 0.0%	0	0	0	–
Laos	**3** 0.2%	2	1	0	0	2	1	**1** 0.2%	1	0	0	–
Singapore	**3** 0.2%	3	0	3	0	0	0	**1** 0.2%	0	0	1	0.02°
Belgium	**2** 0.1%	2	0	0	0	2	0	**0** 0.0%	0	0	0	–
Iran	**2** 0.1%	2	0	0	0	2	0	**0** 0.0%	0	0	0	–
Algeria	**1** 0.1%	1	0	1	0	0	0	**1** 0.2%	0	0	1	0.00°
Belarus	**1** 0.1%	0	1	0	0	0	1	**1** 0.2%	1	0	0	
Bolivia	**1** 0.1%	1	0	1	0	0	0	**1** 0.2%	0	0	1	0.01°
Colombia	**1** 0.1%	1	0	0	0	1	0	**0** 0.0%	0	0	0	–
Nigeria	**1** 0.1%	1	0	1	0	0	0	**1** 0.2%	0	0	1	0.02°
Uruguay	**1** 0.1%	1	0	0	0	1	0	**0** 0.0%	0	0	0	–
Venezuela	**1** 0.1%	0	1	0	0	0	1	**0** 0.0%	0	0	0	–
SES	–	–	–	–	–	–	–	**43** 8.5%	10	11	22	24.60°
Intelsat	–	–	–	–	–	–	–	**33** 6.5%	13	2	18	9.87°
Eutelsat	–	–	–	–	–	–	–	**31** 6.1%	10	1	20	0.62°
Inmarsat	–	–	–	–	–	–	–	**10** 2.0%	1	2	7	9.59°
Arabsat	–	–	–	–	–	–	–	**7** 1.4%	2	1	4	7.53°
Asiasat	–	–	–	–	–	–	–	**6** 1.2%	2	2	2	48.30°
Eumetsat	–	–	–	–	–	–	–	**4** 0.8%	3	1	0	116.10°
ESA	–	–	–	–	–	–	–	**2** 0.4%	0	0	2	0.11°
Azerbaijan	**0** 0.0%	0	0	–	–	–	–	**2** 0.4%	2	0	0	–
Taiwan	**0** 0.0%	0	0	–	–	–	–	**1** 0.2%	0	0	1	0.02°
Turkmenistan	**0** 0.0%	0	0	–	–	–	–	**1** 0.2%	1	0	0	–
RASC	–	–	–	–	–	–	–	**1** 0.2%	1	0	0	–
Bangladesh	**0** 0.0%	0	0	–	–	–	–	**1** 0.2%	1	0	0	–

Table A1.1: Space network licenses matches with GEO satellites and actively station-keeping GEO satellite matches with space network licenses by operator. On the digital version of this document, clicking the icon in the last column of the table redirects readers to the corresponding operator's page on SatelliteDashboard.org, which shows the histories of its actively station-keeping satellites' longitudinal positions, a list of active ITU licenses for their current longitudinal slot, and lists of other objects with which the satellite has engaged in close approaches [12].

A2. Satellite Characteristics Cross-References

The algorithm developed in Section 3 relies on several tables that serve as cross-references between information in space network licenses from the SNL and SNS and the GEO satellite population's launch characteristics. Tables A2.1, A2.2, and A2.3 serve as cross-references for operators, launch vehicles, and spaceports respectively.

18 SpCS Satellite Operator Abbreviation **FULL NAME**	**List of ITU Country Codes for Space Network Matching**
AB ARAB SATELLITE COMMUNICATIONS ORGANIZATION	ARS, KWT, LBY, QAT, UAE, JOR, LBN, BHR, SYR, IRQ, ALG, YEM, EGY, OMA, TUN, MRC, SDN, MTN, SOM, DJI
AC ASIASAT CORP	CHN
AGO REPUBLIC OF ANGOLA	AGL
ALG ALGERIA	ALG
ARGN ARGENTINA	ARG
AUS AUSTRALIA	AUS
AZER AZERBAIJAN	AZE
BELA BELARUS	BLR
BERM BERMUDA	G
BGD PEOPLES REPUBLIC OF BANGLADESH	BGD
BGR REPUBLIC OF BULGARIA	BUL
BOL BOLIVIA	BOL
BRAZ BRAZIL	B
CA CANADA	CAN
CIS COMMONWEALTH OF INDEPENDENT STATES	RUS
EGYP EGYPT	EGY
ESA EUROPEAN SPACE AGENCY	AUT, BEL, CZE, DNK, EST, FIN, F, D, GRC, HNG, IRL, I, LUX, HOL, NOR, POL, POR, ROU, E, S, SUI, G
EUME EUROPEAN ORGANIZATION FOR THE EXPLOITATION OF METEOROLOGICAL SATELLITES (EUMETSAT)	AUT, BEL, BUL, HRV, CZE, DNK, EST, FIN, F, D, GRC, HNG, IRL, I, LVA, LTU, LUX, HOL, POL, POR, ROU, SVK, SVN, E, S, ISL, NOR, SUI, TUR, G
EUTE EUROPEAN TELECOMM. SAT. ORG. (EUTELSAT)	F
FGER FRANCE/GERMANY	F, D
FR FRANCE	F
FRIT FRANCE/ITALY	F, I
GER GERMANY	D
GREC GREECE	GRC
IM INTERNATIONAL MARITIME SATELLITE ORGANIZATION (INMARSAT)	G, GRC, AUT, BEL, CZE, DNK, EST, FIN, F, D, HNG, IRL, I, LUX, HOL, NOR, POL, POR, ROU, E, S, SUI, USA
IND INDIA	IND
INDO INDONESIA	INS
ISRA ISRAEL	ISR
IT ITALY	I
ITSO INTERNATIONAL TELECOMM. SAT. ORG. (INTELSAT)	HOL, USA, G

(continued)

JPN JAPAN	J
KAZ KAZAKHSTAN	KAZ
LAOS LAOS	LAO
MALA MALAYSIA	MLA
MEX MEXICO	MEX
NATO NORTH ATLANTIC TREATY ORGANIZATION	USA
NETH NETHERLANDS	HOL
NIG NIGERIA	NIG
NOR NORWAY	NOR
PAKI PAKISTAN	PAK
PRC PEOPLES REPUBLIC OF CHINA	CHN
RASC REGIONAL AFRICAN SATELLITE COMM. ORG	MTN
RP REPUBLIC OF PHILIPPINES	PHL
SES SOCIÉTÉ EUROPÉENNE DES SATELLITES	LUX, HOL, USA, G, CAN, TKM, MCO, MEX, UAE
SKOR SOUTH KOREA	KOR
SPN SPAIN	E
STCT SINGAPORE/TAIWAN	SNG, CHN
SWED SWEDEN	S
TBD TO BE DETERMINED/UNKNOWN	n/a
THAI THAILAND	THA
TMMC TURKMENISTAN/MONACO	TKM, MCO
TURK TURKEY	TUR
UAE UNITED ARAB EMIRATES	UAE
UK UNITED KINGDOM	G
US UNITED STATES OF AMERICA	USA
USBZ UNITED STATES/BRAZIL	USA, B
VENZ VENEZUELA	VEN
VTNM VIETNAM	VTN

Table A2.1: GEO satellite operator and ITU administration cross-references. When the ITU country symbol of a space network license appears in the same row as a GEO satellite's operator, the administration-operator pair is considered a match by the algorithm described in Section 3.

Launch Vehicle Families and Groupings	List of ITU Launch Vehicles for Space Network Matching
Ariane	ARIANE 2, ARIANE 3, ARIANE 3 FLIGHT 11, ARIANE 3 FLIGHT 13, ARIANE 3 FLIGHT 17, ARIANE 4, ARIANE 4 (44L), ARIANE 4 LAUNCH 41, ARIANE 4 LAUNCH 90, ARIANE 42L, ARIANE 42P, ARIANE 42P F69, ARIANE 42P FLIGHT 40, ARIANE 42P FLIGHT V4, ARIANE 44L, ARIANE 44L H10-3, ARIANE 44LP, ARIANE 44LP (V29), ARIANE 44LP F27, ARIANE 44LP F42, ARIANE 44LP FLIGHT 5, ARIANE 44LP H10-3, ARIANE 44LP-H10+, ARIANE 44P, ARIANE 44P (V103), ARIANE IV, ARIANE-4

Ariane5	ARIANE 5, ARIANE 5 ECA, ARIANE 5 G, ARIANE 5 OR 44L, ARIANE V 141, ARIANE V ECA, ARIANE V13, ARIANE V141, ARIANE V21, ARIANE V28, ARIANE V48, ARIANE V50, ARIANE V81, ARIANE V90, ARIANE V96
Ariane, Ariane5	ARIANE, ARIANE 4 / ARIANE 5, ARIANE 4 OR 5, ARIANE 4 OR ARIANE 5, ARIANE 4/ ARIANE 5, ARIANE 4/ARIANE 5, ARIANE 44L OR 5, ARIANE 44LP OR 5, ARIANE IV / ARIANE V
SRB	ATLANTIS, SPACE SHUTTLE, SPACE SHUTTLE DISCOV, SPACE SHUTTLE STS61B, STS, STS (SHUTTLE), STS 23 (DISCOVERY), STS16
Atlas5	ATLAS V, ATLAS V 400, ATLAS-V
Atlas	ATLAS, ATLAS 1, ATLAS 2A, ATLAS 2AS, ATLAS 2AS (AC117), ATLAS 2AS (AC127), ATLAS 2AS (AC152), ATLAS CENT, ATLAS CENTAUR 11A, ATLAS CENTAUR IIAS, ATLAS CENTAVRO, ATLAS I, ATLAS II, ATLAS II AS, ATLAS IIA, ATLAS IIAS, ATLAS III, ATLAS IIIA, ATLAS IIIB, ATLAS-1, ATLAS2A
Titan	COMMERCIAL TITAN, TITAN 3 (CT-1), TITAN 3C, TITAN IIIC
Delta4	DELTA IIII, DELTA IV
Thor	DELTA, DELTA 2, DELTA 2 FLIGHT 204, DELTA 2 FLIGHT 213, DELTA 2 MISSION 205, DELTA 2- 7925, DELTA 2-6925, DELTA 3, DELTA 7925, DELTA II, DELTA II-7925.8, DELTA- II, THOR DELTA 3914
R-36	DNEPR
Falcon9	FALCON 9 V1.1, FALCON HEAVY
H2	H-IIA
DF5	LM-3, LM-3A, LM-3B, LONG MARCH -3A, LONG MARCH 2E, LONG MARCH 3, LONG MARCH 3A, LONG MARCH 3B, LONG MARCH 3BE, LONG MARCH 3C, LONG MARCH 5, LONG MARCH-3, LONG MARCH-3A, LONG MARCH-3B, LONGMARCH-3C
Proton	PROTON, PROTON BREEZE M, PROTON D-1-E, PROTON K, PROTON K/BLOCK DM, PROTON M, PROTON M BREEZE M, PROTON M/BREEZE M, PROTON-D-1-E, PROTON-D1, PROTON-K, PROTON/BREEZE M
PSLV	PSLV, GSLV
ASLV, PSLV, GSLV3	SLV
R-7	SOYUZ, SOYUZ U
SRB, Atlas5, Delta4, Falcon9, Titan, Thor, Atlas	US GOVERNMENT, US GOVERNMENT VEHICL, USA GOV'T VEHICLE, USA GOVERNMENT, USA GOVERNMENT VEHIC, USA GOVMENT VEHICLE, US GOV VEHICLE
Zenit	ZENIT 3 SL, ZENIT 3-SL, ZENIT 3SL, ZENIT-2, ZENIT-3SL, ZENIT-3SLB

Table A2.2: GEO satellite launch vehicle family and ITU due diligence filings' launch vehicle cross-references. When the planned launch vehicle listed in an ITU space network filing appears in the same row as a GEO satellite's launch family, the vehicle-family pair is considered a match by the algorithm described in Section 3.

18 SpCS Spaceport Abbreviation FULL NAME	**ITU Launch Site for Space Network Matching**
AFETR AIR FORCE EASTERN TEST RANGE	CAPE CANAVERAL
FRGUI FRENCH GUIANA	KOUROU
SEAL SEA LAUNCH	SEA LAUNCH
SRI SIRHARIKOTA	SRIHARIKOTA
TNSTA TANEGASHIMA SPACE CENTER	TANEGASHIMA
TTMTR TYURATAM MISSILE AND SPACE COMPLEX	BAIKONUR
WSC WENCHANG SATELLITE LAUNCH CENTER	WEN CHANG
XSC XICHANG SPACE CENTER, CHINA	XICHANG

Table A2.3: GEO satellite spaceport and ITU due diligence filings' launch site cross-references. When the planned launch site listed in an ITU space network filing appears in the same row as a GEO satellite's spaceport, the spaceport-site pair is considered a match by the algorithm described in Section 3.