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Review

Large Constellations of Small Satellites: A Survey of Near Future Challenges and Missions

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Abstract: Constellations of satellites are being proposed in large numbers; most of them are expected to be in orbit within the next decade. They will provide communication to unserved and underserved communities, enable global monitoring of Earth and enhance space observation. Mostly enabled by technology miniaturization, satellite constellations require a coordinated effort to face the technological limits in spacecraft operations and space traffic. At the moment in fact, no cost-effective infrastructure is available to withstand coordinated flight of large fleets of satellites. In order for large constellations to be sustainable, there is the need to efficiently integrate and use them in the current space framework. This review paper provides an overview of the available experience in constellation operations and statistical trends about upcoming constellations at the moment of writing. It highlights also the tools most often proposed in the analyzed works to overcome constellation management issues, such as applications of machine learning/artificial intelligence and resource/infrastructure sharing. As such, it is intended to be a useful resource for both identifying emerging trends in satellite constellations, and enabling technologies still requiring substantial development efforts.

Keywords: large constellations; operations; traffic; regulation; spacecraft

1. Introduction

The idea of a constellation of satellites appeared in the market about twenty years ago with Iridium and Globalstar as pioneering examples. They offered worldwide communication links competing with the terrestrial cellular network, having, however, limited success due to service costs mainly [1,2]. We can now say that at that time the business model was not sustainable due to the small market and high initial and maintenance costs.

Access to space is now broadening thanks to technology miniaturization and design experience. With a tremendous forecasted increase in the launch rate for small satellites (from pico-sized to mini-sized) [3], constellations are getting attention again from sustainable businesses [4].

Constellations have their greatest potential in the communication field. The upcoming era of the Internet-Of-Things requires the communication infrastructure to handle huge amounts of data and to guarantee service in any geographical position. Constellations, however, also have great potential in weather science, safety/security and disaster monitoring [5].

In the rapidly emerging business of satellite constellations, it is important to track and update the information about players and trends to guide future developments. While for other emerging satellite related markets such as the one of the nanosatellite revolution, several surveys have already been published, both technical [6] or market oriented [3], the authors are not aware of a similar effort towards satellite constellations. As remarkable exception, the very recent work in [7], is mainly devoted to Space Traffic Management. In [8] constellations are instead considered as part of the wider context of distributed satellite systems (DSS). They are characterized morphologically as those DSS having high degrees of homogeneity and physical separation, but low functional and operational interdependence. The paper provides a historical perspective of DSS, their taxonomy, and an overlook of technological solutions at subsystem and system levels. However, it lacks a detailed review of constellations.

In this review paper, we aim at the perspective of matching technical needs and technology availability for large constellations, while providing at the same time a detailed survey of the upcoming satellite constellations, and that is all articulated as follows. The main trends are examined in Section 2, considering the targeted application field, the constellation size and the expected time-to-completion. In addition to statistical aspects, technical challenges are also outlined and then expanded in Section 3. Issues, such as constellation management, communication efficiency, space traffic and deployment strategies, are analyzed after reviewing the work that has been done so far in the literature.

In Section 4 conclusions are drawn, wherein we outline the main analogies between the upcoming constellations and the most promising trends for the solutions to technical challenges.

2. Satellite Constellation Players

There have been few attempts to propose large satellite constellations for commercial purposes in the past few decades (from ca. the late-90s to 2015). Among them were the companies ViaSat, Boeing, Samsung, Yaliny [9], Globalstar [10] and Iridium [11]. In all cases, the target application was in the communication field, aimed at providing global connectivity with different strategies: medium Earth orbit (MEO) or low Earth orbit (LEO) constellations, and large or small numbers of satellites. All of them have been delayed [12], restyled [13] or have failed [14]. These proposals are included anyway in the upcoming statistical analysis, for possibly being part of future or current space traffic. Non-commercial constellations for Global Navigation Satellite System (GNSS) purposes, namely, the GPS, GLONASS, Galileo and BeiDou are included as well. Constellations in GEO orbit, such as IRNSS, are instead left out of the statistics.

In the last few years, the proposals of satellite constellations have experienced a tremendous increase with more than one hundred companies trying to succeed in different markets with different approaches. At the time of writing, more than 90 companies or agencies (other than older attempts, some of which are mentioned above) have been found proposing satellite constellations.

The target fields of application can be grouped in three categories: Earth observation (EO) (science or business oriented), space observation (SO) and communications (Comm).

Figure 1 clearly suggests that applications in EO (such as weather, disaster and alert monitoring) and communications (Internet-of-Things, machine-to-machine applications) are the driving sectors for the constellations being proposed.

The distribution of some constellation characteristics, such as the number and size of satellite platforms and expected time to completion, is also of interest. Figure 2 depicts the trend of the number of proposed constellation satellites expected to be in orbit in the next years. Note that the number of satellites and the expected year of completion for a constellation are not always available, probably due to a lack of confidence from the companies. Those companies have been assigned to the category "NC" in the figure. Additional details and references are given in Appendix A. Furthermore, in preparing Figure 2 the assumption of a constant deployment rate was made for each constellation. This assumption is made necessary because of the lack of information on the deployment plans by many companies. Therefore, for each constellation, the difference between the year of the first satellite launch (occurred or planned) and the expected year of completion has been considered as the deployment window. By dividing the number of satellites in the constellation by the deployment window, a constant deployment rate was obtained which was then used to populate Figure 2.

Although some constellations still have unpublished years of completion, many are expected to be in orbit by 2022 with a peak in 2020. This reflects the rapid development of the market and the high competitiveness which stresses the shortening of the time-to-market. A clear outlier is the Starlink constellation from SpaceX, with a 4425-element constellation dominating the columns of the years 2019 to 2024—the year in which it is expected to be completed. This delay in the time-to-market is probably due to the large amount of satellites that are expected to be placed.

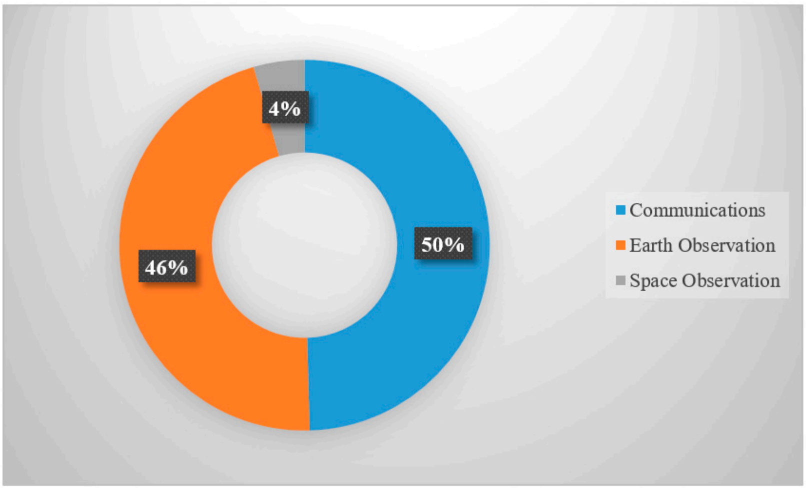

Figure 1. Percentages of proposed constellations in different market fields.

Looking at the cumulative sum, the number of satellites in orbit is going to increase more than linearly with about 8000 spacecraft in orbit in 2024 due to constellations only. The resulting volume of traffic opens up a question about whether it is possible to sustain this development or not, under several points of view. For example, the current ground segment infrastructures will probably not be able to monitor and control such a large number of satellites. A major satellite ground service provider such as KSAT is already investing for infrastructure enlargement [15]. At the same time, constellation management shall be enhanced to make an efficient use the new infrastructure. This requires new operational architectures towards higher automation, either onboard or on ground, involving, for instance, artificial intelligence and virtual reality [16,17]. A second concern involves the communication, with the RF spectrum becoming possibly overcrowded and the required data-throughput increasingly larger. Lastly, but probably most importantly, the space traffic and debris issues, which may prevent the safe and successful operation of spacecraft [17].

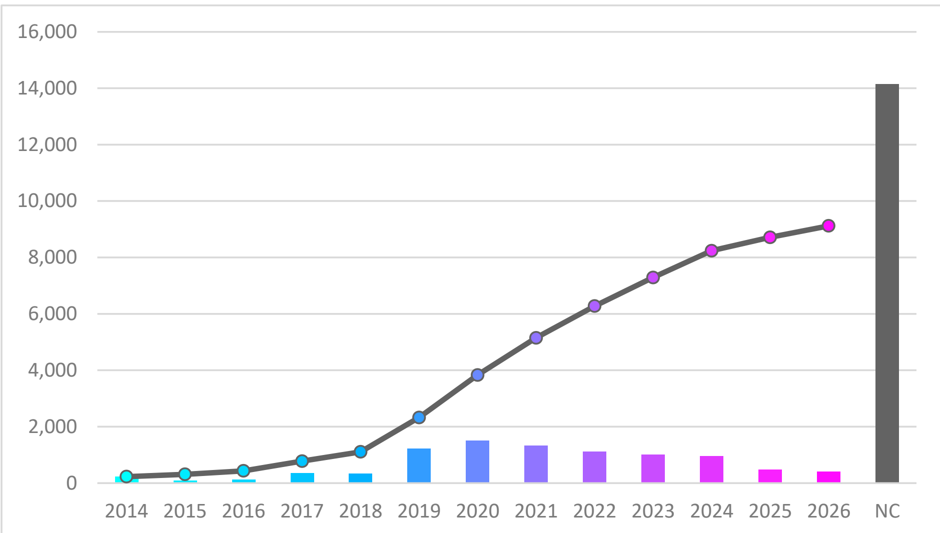

Figure 2. Expected time evolution of in orbit spacecraft due to constellations. Colored histogram bars represent the estimated number of satellites launched yearly (see Table A1 in Appendix A for details). Black, dotted line represents cumulative sum. Not-classified (NC) stands for companies that have not published expected time-to-service.

As far as the size is concerned, the proposed constellations are quite widespread. According to Figure 3, roughly half of the constellations are relatively small, containing less than 50 elements. Constellations with numbers of elements between 50 and 150 elements appear to be quite appealing as well, with a 22% share. Larger size slots are instead of particularly low interest. Finally, a considerable 17% features non-declared sizes, as anticipated.

Satellite sizes show a clear bias towards micro and nano classes, reflecting the trend towards the miniaturization of satellite platforms in general (Figure 4). Although 35% of the constellation projects do not declare size, 32% belong to nano-class and 18% to micro-class. Pico, mini, medium and large classes reflect the minority, with a total share of 15%. This means that constellations are going to be composed of satellites weighting mainly from 1 to 100 kg.

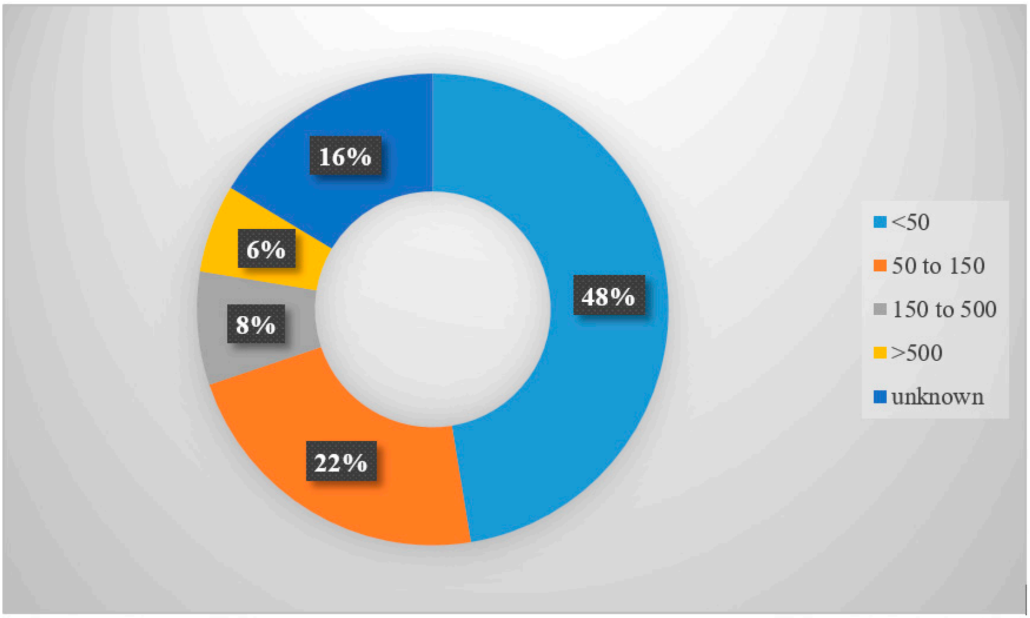

Figure 3. Constellations by satellite numbers.

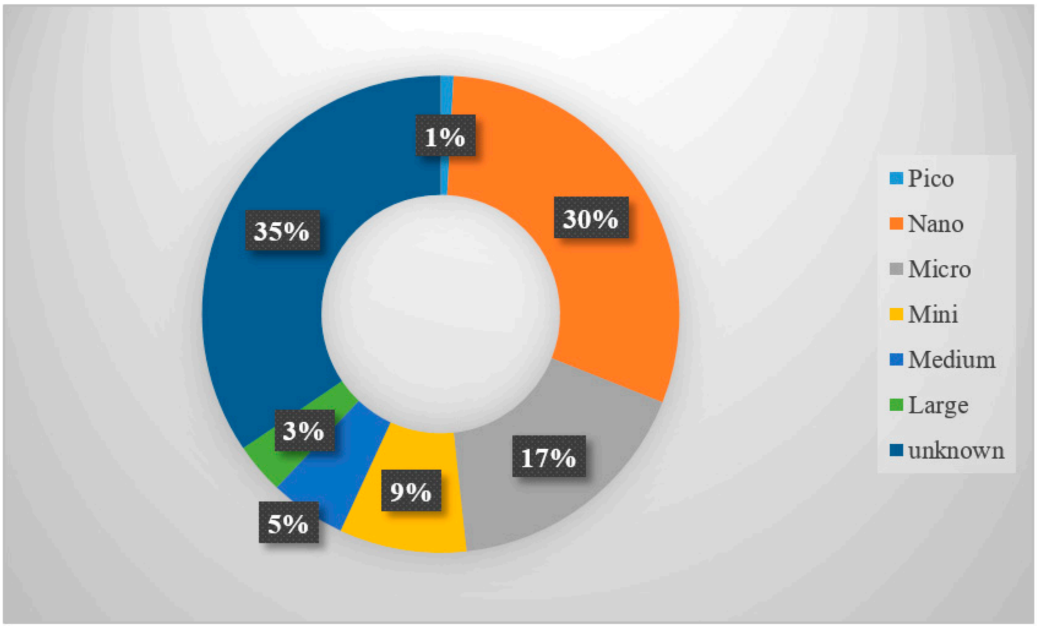

Figure 4. Constellations by satellite sizes: mass < 1 kg = pico; 1 kg < mass < 10 kg = nano; 10 kg < mass < 100 kg = micro; 100 kg < mass < 500 kg = mini; 500 kg < mass <1000 kg = medium, mass > 1000 kg = large.

3. Future Challenges

Large constellations will require a paradigm shift with respect to the way space missions are currently handled, with major challenges involving technical, management and regulatory aspects. The main ones are discussed hereafter by analyzing the work that has been done so far and outlining possible future developments.

3.1. Constellation Management

With such a number of active elements in orbit, their management is a fundamental point of interest. Since constellations have not been widely used in the past, not too much work has been done in this sense. However, some key experiences can certainly be located in projects such as Galileo (European GNSS) [18], Globalstar constellations [19] and other GNSS constellations (GPS, BeiDou, etc.).

In [18,19] different strategies have been explored, all driven by the common objective of enhancing the level of automation, so that more satellites will not translate into a proportional increase of managing effort. Proposed solutions fall into two main categories:

(a) Optimization of automatic satellite tracking (such as telemetry download).
(b) Automatic failure detection, so that the operator does not need to manually check the satellite's status of health.

Still, there are a great number of non-automatic operations left to do; [19,20] pointed out some desired operational improvements, along with lessons learnt from operating constellations. Some points have been found to be very real and worth being analyzed here:

1. Splitting between payload operations and spacecraft operations, possibly with dedicating ground segments to each of the two.
2. Increasing automation onboard the spacecraft, which is not always possible due to satellite size constraints. In the latter case, expert systems (intended as an ensemble of algorithms, and machines aiding the operator's decisions, usually associated with artificial intelligence, are applied for high level tasks—prediction, planning, diagnosis, repair, etc.) shall be deployed on ground.
3. Taking not only the ground segment into account but also the operations from the initial phases of the constellation design.
4. Expert systems shall be designed to assist operators and keep the workload constant during constellation operations, e.g., mitigating the heavier workload during launch and early orbit phase.

As per point 2, the need for automation, a relevant example is the collision avoidance assessment and maneuver planning, which is now largely manual. This problem is addressed in [7], where the need for an increased accuracy in orbit determination is pushed forward as a means to reduce false alarms and implement automatic orbital corrections.

In favor of point 2, the authors of [21] propose an onboard automated management system, based on artificial intelligence. In their implementation, failures are not only detected, but also handled automatically towards a resolution along with a re-scheduling of the original plan. The main drawback of the proposed approach is its need for an intersatellite-link, which is usually not affordable for low-cost strategies. Moreover, it implies intensive intersatellite communication contributing to RF spectrum crowding.

Another approach is proposed in [22] for an Earth Observation constellation. It consists of an autonomous (re-)planning strategy for maximizing the total science return of observations over time. Despite not reaching the degree of automation as in [21], the automatic re-planning decreases the ground workload, allowing the operator to concentrate more on the goal, rather than the path to it. Thus, this is also in favor of point 4.

Regarding point 3, a few aspects that shall be included at the beginning of the constellation design operation-wise will be now discussed. The automation logic given above is one example. In fact, it impacts greatly on the development complicating the space segment design, at least software-wise.

The replacing strategy is another operational aspect that must be taken into account from the beginning: a replacing or spare strategy is the policy adopted by the operators to substitute failed or terminated satellites of the constellation. Most of the constellations need such a policy to guarantee a 24/7 service, affecting launching phases and satellite design (reliability). The authors in [23] give an example of work in this sense through the application of inventory management approach to the space field. They propose a set of parking orbits and in-plane spares which are refurnished from ground following an optimal policy (i.e., minimize the total Expected Spare Strategy Cost). These spare satellites are then moved into the constellation when needed. Notice that the reliability of the constellation can be regarded also from a building process perspective as stated in [24] (rather than satellite design only) which suggests, for instance, adopting a Failure Mode and Effect Analysis for a robust mass production.

The deployment strategy is also fundamental to be included in point 3, given the constellation size trend and the competitiveness of the field. Spacecraft deployment must be accounted for since the beginning because it has a significant impact on the lifecycle cost. In fact, it affects both the number of launches and the complexity of the satellite to be launched. In principle one launch for every orbital plane is needed, also the complexity of the onboard propulsion system (if any) changes based on the post-launch operations to be performed.

Few interesting works in this respect are [25–28]. The approach studied in [25] consists of deploying the spacecraft gradually as they are needed by the market, which is shown to reduce the life cycle cost of a constellation significantly, of about 20% when applied to the Globalstar case study. Similarly, [28] consider a staged deployment which is optimized using genetic algorithms. This approach seems to be particularly appealing as it makes the constellation size adaptable to the market reaction, which is very difficult to predict as Iridium and Globalstar experiences have shown.

Other efficient deployment strategies are compared in [26] such as J2 driven deployment and carrier-vehicle deployment. These methods allow one to configure the orbits in space avoiding multiple launches. The use of Earth-Moon Lagrangian point L1 is envisaged in [27], however, this solution seems to be convenient only in combination with carrier vehicles.

3.2. Communication Issues

Communication is a key point when operating a constellation, in fact:

- On-Board Automation is unlikely to grow to the point of allowing fully autonomous fleet management: a large amount of satellites will thus need to communicate frequently with ground.
- Constellations are designed usually for real time—24/7-purposes, requiring data down/up-load at any time.

The above two points rise concerns about Radio Frequency (RF) spectrum partitioning. An overcrowded RF spectrum may indeed cause physical interference of adjacent RF signals. At the same time, the traffic capacity of the communication infrastructure shall grow in parallel with the data volume travelling in the RF channels.

The research community is actively working towards these two aspects. One of the most promising approach towards infrastructure optimization is the sharing and integration between space and ground communication networks, especially in view of the upcoming 5G service [29]. Work in this sense can be found since the turn of the century, see e.g., [30] where the possibility of integrating a satellite network with a terrestrial network is envisaged using an IP-based communication. Few years later, authors of [31] provided a survey of mobile satellite systems endorsing IP-based communication, discouraging however communication satellites other than GEO, mainly for cost efficiency. Despite the miniaturization trend in LEO spacecraft was already established by then, the recommendation towards GEO is not surprising, given the negative experiences of the firsts LEO constellations like Iridium and Globalstar. More recently, due to the rising interest in satellite constellations authors of [32,33] brought the attention again onto the potential of LEO satellites as communication infrastructure. The first studies the integration of the 5G ground network with a space-based network emphasizing its potential for global connectivity. The second studies the efficient implementation of inter-satellite link through a routing algorithm. The algorithm takes into account maximum available link time and remnant bandwidth to increase the total traffic capacity of the network in the presence of handover.

A more practical solution to the frequent communication needed by low-autonomy spacecraft is a conventional network of existing ground stations. This solution could be already feasible upon standards definition for communication (e.g., CCSDS) and hardware interfaces, in fact ground station providers like KSAT or KRATOS are going towards this direction. KRATOS for example designed a device called *quantumCMD* [34], a small computer able to operate up to 4 satellites when integrated in a ground station. The power of the device is its scalability with number of satellites and ground stations.

Solutions against the increasingly crowded spectrum are devoted mainly towards (a) spectrum sharing and (b) enhancement of regulation. Examples can be found in [35], where the possibility of a Database-Assisted spectrum sharing is pushed forward. Using this approach, the temporarily unused spectrum could be reallocated for a more efficient use. Note that also [35] uses the keyword "sharing" between satellite and terrestrial networks.

A completely different approach to avoid RF spectrum overcrowding consists of moving to the optical part of the spectrum. Optical communication promises higher data rates using smaller and lighter terminals, even though due its high sensitivity to atmospheric conditions it is more suited for free-space inter-satellite links rather than satellite-to-ground [36] (enabling communication between constellation elements is an asset by its own, though). An optical communication system conceived for LEO constellations is described in [37] and is currently at an advanced development stage.

3.3. Space Traffic Management

Among the issues to be faced in the "constellation race" the space traffic management is probably the most critical, yet not directly faced. [7,38] are the few works authors are aware of that discuss this topic, the first specifically within the large constellations framework and the second in general.

Part of this topic is closely related to space debris. Debris are already a problem that is being faced actively with surveillance networks (e.g., the JSpOC, Joint Space Operation Center [39]) and avoidance maneuvers from the spacecraft operators. Will this network be able to withstand, i.e., generate alerts and provide further assistance, also for the future traffic? What happens if a constellation is very valuable but cannot embark a propulsion system for collision avoidance? First steps towards answering these questions are found in very recent studies: [7] discusses the changes in LEO population environment due to large constellations, while authors of [40] advocate the need for updating state-of-the art space debris modelling as a result of the evolving debris environment.

A preventive approach is already taking place thanks to debris mitigation policies i.e., making the spacecraft reenter at the end of its life. [40] suggests that the constancy of the rate at which spacecraft fragmentations (historically the main cause of space debris) occurs, despite the drastic increase in the number of orbiting spacecraft [41], is an indication that mitigation efforts put in place are being successful. Whether or not such efforts will remain effective when hundreds of dismissed or failed constellation satellites will be deorbiting almost simultaneously, is still an open point.

Alternative solutions to the debris problem include active removal [42] and space-based surveillance networks [43,44]. On-Orbit servicing is a further option to decrease the amount of failed or dead satellites that become a debris. Its implementation, however, is still costly and technically challenging [45].

Regulatory aspects of space traffic management are instead poorly covered. Currently, once a free orbital slot has been identified, the common practice consists of seeking for a technically and economically viable solution to reach such a slot. Not much attention, instead, is payed to interferences affecting other operators, that might be caused while the spacecraft are reaching the target orbit or during de-orbiting at the end of life. The authors in [7] envisage an architecture similar to the air traffic management with traffic zones (orbital slots) and "flight plans." Though up to now it has been safe to assume that space is so large that satellite operations do not interfere with each other, this may not be true in the near future. For instance, with thousands more spacecraft in orbit, an Earth observation satellite may find unexpectedly another one in its field of view, or a region of space may become so overcrowded as to impact the quality of space observations from ground. One such event was indeed experienced after the launch of the first Starlink satellites (Figure 5).

Besides the regulatory part, there are also technical challenges to be overcome. In [46,47] for instance, machine learning through support vector machines is used both to monitor satellite health and address management issues, highlighting a great potential of neural networks for enhancing space traffic management. Other approaches, such as space transponders and enhanced tracking with corner reflectors or onboard GPS receivers, are pushed forward in [7].

Novel concepts of conjunction assessment services are also on their way. In [38] a prototype of a ground-based service that can interface with all subscribed satellite operators (scalable solution) was presented. Besides integrating different object databases and giving alerts similarly to JSpOC, it can compute the most suitable avoidance maneuvers. Thanks to the global situational awareness of the service, such a maneuver can ensure minimum fuel consumption while avoiding “cascade maneuvers.” Moreover, after suggesting the maneuver directly to the involved spacecraft operators, it can update its database and inform the other operators when the maneuver is accomplished.

Another interesting attempt is discussed in [48], wherein the Australian Government is financing a conjunction assessment service featuring a ground-based laser “deviator.” The aim is to maneuver small uncooperative objects remotely from ground using a laser beam, which is theoretically feasible but with great technical challenges due to the laser power needed.

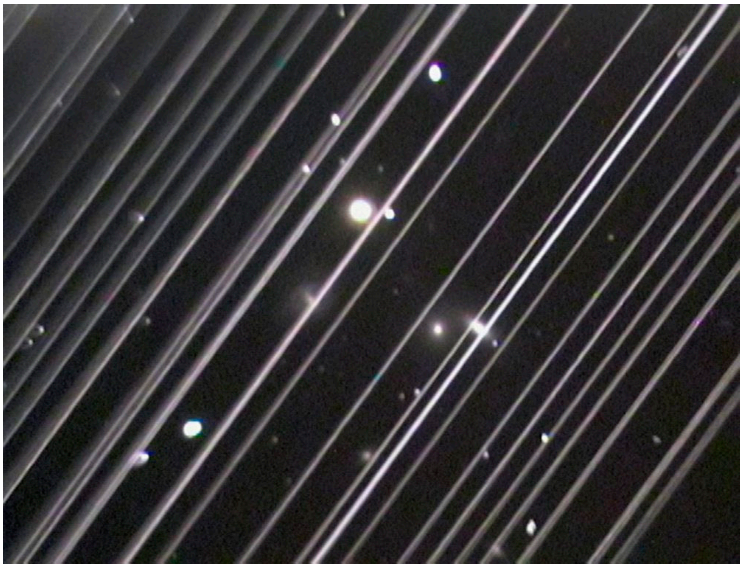

Figure 5. Galaxy group NGC 5353/4 seen with a telescope at Lowell Observatory in Flagstaff with Starlink satellites passing in front, Arizona, on 25 May 2019 (Courtesy of EarthSky Voices).

4. Discussion

The increasing trend of launching very small satellites into space has been clear and well established for the last two decades. Smaller satellites are in turn paving the way to constellations, which are gaining widespread interest. Spacecraft constellations are appealing, especially in three fields, namely, (i) communications, for global coverage, (ii) Earth observation, for near real time measurements and (iii) space observation for continuous monitoring/surveillance.

During this survey, about one hundred companies have been found proposing constellations with varying numbers of satellites. Satellite sizes range mainly from nano to micro-sizes, i.e., from 1 kg up to 100 kg. Most of them are expected to be active in orbit before 2025. The most common number of elements for the constellations is below 150 units.

A review was carried out on the challenges that satellite constellations will have to face to become more sustainable, with a focus on three categories: constellation management, communication and space traffic. The level of maturity reached by these three areas is, however, not homogeneous: communication is probably the most matured, where relevant work is being done concerning infrastructure integration and protocol efficiency. Some significant past experience in constellation management was reviewed during this survey; still, the need for an improved level of automation is clear. In this respect, artificial intelligence seems to be a valuable option, together with infrastructure sharing for rapid development and commercial viability. On the other hand, space traffic management is mostly unprepared, with significant developments only in terms of debris countermeasures. Some extensions of the air traffic regulation are expected in the years to come to mitigate the current free-space policy covered by the Outer Space Treaty.

Although many technical challenges are still being addressed, the amount of work that has been analyzed during this review suggests good chances of success for large constellation missions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of constellations surveyed in this work. "?" stands for unknown; "*" stands for "dormant or cancelled project".

Company	No. Sats	Sats Size	Orbit	Year (Operative)	Reference
Globalstar Inc.	48	Medium	LEO	?	[49]
Iridium Inc. - Aieron	75	Medium	LEO	2019	[50]
OneWeb	648	Mini	LEO	?	[51]
O3b (SES mPower)	27	Medium	MEO	2021	[52]
Orbcomm	11	Mini	LEO	2015	[53]
Gonets SS (Roscosmos)	11	Mini	LEO	2014	[54]
SpaceX	4425	Mini	LEO	2024	[55]
Telesat	117		LEO	2021	[56]
BlackSky Global	60	Micro	LEO	2021	[57]
SPIRE Global	175	Nano	LEO	2020	[58]
Planet Labs	5		LEO	2008	[59]
Planet Labs	12	Nano	LEO	2015	[59]
Planet Labs	20	Nano	LEO	2016	[59]
Planet Labs	12	Nano	LEO	2016	[59]
Planet Labs	48	Nano	LEO	2017	[60]
Planet Labs (Terra Bella)	15	Micro	LEO	2017	[61]
Kepler Communications, Inc.	140	Nano	LEO	2022	[62]
Kineis	25	Micro	LEO	2022	[63]
ExactEarth	67	Nano	LEO	2018	[64]
Planet Labs	88	Nano	LEO	2017	[65]
Planet Labs	20	Nano	LEO	2019	[66]
Astro Digital	?	Micro	LEO	?	[67]
BRITE partners	5	Nano		2014	[68]
GHGSat, Inc.	3	Micro		2020	[69]
Satellogic	60	Micro	LEO	2020	[70]
Space View	16	Medium	LEO	2022	[71]
CASIC	156		LEO	2025	[72]
Leosat (Thales Alenia)	108	Large	LEO	*	[73]

Table A1. *Cont.*

Company	No. Sats	Sats Size	Orbit	Year (Operative)	Reference
Sky and Space Global	200	Nano	LEO	2020	[74]
GeoOptics	24	Nano	LEO	?	[75]
NOAA	12	mini	LEO	2020	[76]
PlanetIQ	18	Micro	LEO	2020	[77]
Zhuhai Orbita Control Engineering Ltd.	34	Micro	LEO	2020	[78]
Canon	100	Micro	LEO	?	[79]
Helios Wire	28	Micro	LEO	2023	[80]
Swarm Technologies	100	Pico		?	[81]
Iceye (BridgeSat)	18	Micro	LEO	2020	[82]
Analitical Space	?		LEO	?	[83]
Hiber	48	Nano	LEO	?	[84]
Fleet Space	100	Nano	LEO	2022	[85]
Audacy	3		MEO	2020	[86]
ELSE	64	Nano	LEO	2021	[87]
AISTech	102	Nano	LEO	?	[88]
AISTech	18	Nano	LEO	?	[88]
HawkEye360	21		LEO	?	[89]
Axelspace	50	Micro	LEO	2022	[90]
Capella Space	36	Micro	LEO	?	[91]
Karten Space	?	Nano	LEO	?	[92]
UnseenLabs	?		LEO	?	[93]
NSLComm	60	Nano	LEO	?	[94]
EightyLEO	?	Mini	LEO	2022	[95]
UrtheCast	24		LEO	2021	[96]
Orbital Micro System	40	Micro	LEO	?	[97]
Lacuna Space	32	Nano	LEO	?	[98]
Hera Systems	50		LEO	?	[99]
CASC (xinwei)	300		LEO	2025	[100]
SRT Marine	?		LEO	*	[101]
SatRevolution	1024	Nano	LEO	2026	[102]
Commsat Technology Development Co. Ltd.	72		LEO	2022	[103]
Aerial and Maritime	80	Nano	LEO	2021	[104]
Harris	12	Nano	LEO	?	[105]
Earth-i	15	Mini	LEO	?	[106]
LinkSure Network	272		LEO	2026	[107]
Synspective	25	Mini	LEO	?	[108]
Space Systems Engineering Ukraine	?			?	[109]
Astrome	200	Mini	LEO	2023	[110]
Cloud Constellation Corp.	10		LEO	?	[111]
Transcelestial	?	Nano	LEO	?	[112]
Kleos Space	4		LEO	2019	[113]
HyperSat	6	Micro	LEO	*	[114]
Galaxy space	1000		LEO	?	[115]
ChinaRS	10	Micro	LEO	2021	[116]
Laser fleet	?		LEO	2022	[117]
XpressSAR	4			2022	[118]
Orbital oracle Technologies	100	Nano	LEO	2024	[119]
Methera Global	16		MEO	2022	[120]
Trident Space	48	Mini	LEO	2026	[121]
VEOWARE	?		LEO	2022	[122]
Umbra Lab	12		LEO	?	[123]
EarthNow	?		LEO	?	[124]
OQ Technology	?	Nano		?	[125]

Table A1. *Cont.*

Company	No. Sats	Sats Size	Orbit	Year (Operative)	Reference
Tekever	12	Micro	LEO	?	[126]
KLEO Connect	300		LEO	?	[127]
NorStar NorthStar	40	Medium		2021	[128]
Laser Light	12		MEO	2020	[129]
Koolock	?			?	[130]
ROSCOSMOS	10			2023	[131]
Hypercubes	?	Nano		?	[132]
ROSCOSMOS	288		LEO	2025	[133]
B612 Foundation	?	Micro		?	[134]
NASA	8	Micro	LEO	2017	[135]
CG Satellite	60		LEO	2020	[136]
Amazon	3236		LEO	?	[7]
Viasat	20		MEO	*	[13]
Iridium Inc.	66		LEO	2000	[11]
Boing	2956			*	[9]
Samsung	4600		LEO	*	[9]
Yaliny	135			*	[9]
Globalstart inc.	48		LEO	1999	[10]
OmniEarth	18		LEO	*	[137]
COMMStellation	72	Micro	LEO	*	[138]
Myriota	50	Nano	LEO	?	[139]
ADASpace	192		LEO	2021	[140]
Ubiquitilink	24			2021	[141]
ZeroG Lab	132		LEO	?	[142]
Stara Space	?	Nano	LEO	?	[143]
Hyperion	?	Nano	LEO	?	[144]
Horizon Technologies	10	Nano	LEO	?	[145]
SpaceFab.US	16	Nano		?	[146]
HEO Robotics	12	Nano	HEO	?	[147]
Artemis Space	?	Nano		?	[148]
Pixxel	?	Nano	?	?	[149]
US space Force	75	Large	MEO	1993	[150]
VKS	24	Large	MEO	1995	[151]
ESA	30	Medium	MEO	2020	[152]
CNSA	35	Large	MEO	2020	[153]

References

1. McIntyre, D.A. The 10 Biggest Tech Failures of the Last Decade—Failure to Launch Iridium. 14 May 2009. Available online: http://content.time.com/time/specials/packages/article/0,28804,1898610_1898625_1898640,00.html (accessed on 28 June 2019).
2. Glasner, J. Globalstar: Broke But Not Out. 14 November 2001. Available online: https://www.wired.com/2001/11/globalstar-broke-but-not-out/ (accessed on 20 July 2019).
3. Williams, C.; Doncaster, B.; Shulman, J. *2018 Nano/Microsatellite Market Forecast*, 8th ed.; SpaceWorks Enterprises Inc.: Atlanta, GA, USA, 2018.
4. Lal, B.; de la Rosa, E.B.; Behrens, J.; Corbin, B.; Green, E.K.; Picard, A.A.J.; Balakrishnan, A. *Global Trends in Small Satellites*; IDA Science and Technology Policy Institute: Alexandria, VA, USA, 2017.
5. Sandaua, R.; Brieß, K.; D'Errico, M. Small satellites for global coverage: Potential and limits. *ISPRS J. Photogramm. Remote Sens.* **2010**, *65*, 492–504. [CrossRef]
6. Panga, W.J.; Bo, B.; Meng, X.; Yu, X.Z.; Guo, J.; Zhou, J. Boom of the CubeSat: A Statistic Survey of CubeSats Launch in 2003–2015. In Proceedings of the 67th International Astronautical Congress (IAC), Guadalajara, Mexico, 26–30 September 2016.
7. Muelhaupt, T.J.; Sorge, M.E.; Morin, J.; Wilson, R.S. Space traffic management in the new space era. *J. Space Saf. Eng.* **2019**, *85*, 51–60. [CrossRef]

8. Selva, D.; Golkar, A.; Korobova, O.; Cruz, I.L.; Collopy, P.; de Weck, O.L. Distributed Earth Satellite Systems: What Is Needed to Move Forward? *J. Aerosp. Inf. Syst.* **2017**, *14*, 412–438. [CrossRef]
9. Henry, C. LEO and MEO Broadband Constellations Mega Source of Consternation. 13 March 2018. Available online: https://spacenews.com/divining-what-the-stars-hold-in-store-for-broadband-megaconstellations/ (accessed on 20 July 2019).
10. Globalstar Completes 48-Satellite Constellation. 23 November 1999. Available online: https://www.wirelessnetworksonline.com/doc/globalstar-completes-48-satellite-constellati-0001 (accessed on 28 June 2019).
11. Flarewell. 2019. Available online: https://www.iridium.com/flarewell/ (accessed on 20 July 2019).
12. Henry, C. Boeing Constellation Stalled, SpaceX Constellation Progressing. 27 June 2018. Available online: https://spacenews.com/boeing-constellation-stalled-spacex-constellation-progressing/ (accessed on 20 July 2019).
13. Henry, C. Viasat Shrinks MEO Constellation Plans. 5 November 2018. Available online: https://spacenews.com/viasat-shrinks-meo-constellation-plans/ (accessed on 28 July 2019).
14. Lim, J.; Klein, R.; Thatcher, J. GOOD TECHNOLOGY, BAD MANAGEMENT: A CASE STUDY OF THE SATELLITE PHONE INDUSTRY. *J. Inf. Technol. Manag.* **2005**, *16*, 48–55.
15. Eilerten, B.; Krynitz, M.; Olafsson, K. NewSpace—Forcing a rethink of ground networks. In Proceedings of the 14th International Conference on Space Operations, Daejeon, Korea, 16−20 May 2016; p. 2599.
16. Monteverde, J.; Bullock, M.; Schulz, K.-J. Operations Innovation. In Proceedings of the Industry Workshop, ESA-ESOC, Darmstadt, Germany, 17−18 January 2019. Available online: https://atpi.eventsair.com/QuickEventWebsitePortal/19c10---industry-workshop/website/ExtraContent/ContentPage?page=4 (accessed on 29 July 2019).
17. Babrinsky, N. Mission Operations Ground Segments Space Safety. In Proceedings of the Industry Workshop, ESA-ESOC, Darmstadt, Germany, 17−18 January 2019. Available online: https://atpi.eventsair.com/QuickEventWebsitePortal/19c10---industry-workshop/website/ExtraContent/ContentPage?page=4 (accessed on 29 July 2019).
18. Porretta, M. Method and Apparatus for Determining a Schedule for Contact with a Constellation of Satellites. U.S. Patent No. 10,551,503, 1 February 2018.
19. Smith, D.; Hendrickson, R. Mission Control for the 48-Satellite Globalstar Constellation. In Proceedings of the MILCOM'95 IEEE, San Diego, CA, USA, 5–8 November 1995; Volume 2, pp. 828–832.
20. Howard, J.; Oza, D.; Danford, S.S. Best Practices for Operations of Satellite Constellations. In Proceedings of the 9th International Conference on Space Operations, Rome, Italy, 19–24 June 2006.
21. Robert, R.A.; Ryan, H.T.; John, M.L. Distributed Satellite Constellation Planning and Scheduling. In Proceedings of the FLAIRS Conference AAAI, Key West, FL, USA, 21–23 May 2001; pp. 68–72.
22. Abramson, M.; Carter, D.; Kolitz, S.; Ricard, M.; Scheidler, P. Real-Time Optimized Earth Observation Autonomous Planning. In Proceedings of the NASA Earth Science Technology Conference, Houston, TX, USA, 9–12 October 2002; pp. 68–72.
23. Jakob, P.; Shimizu, S.; Yoshikawa, S.; Ho, K. Optimal Satellite Constellation Spare Strategy Using Multi-Echelon Inventory Control. *J. Spacecr. Rocket.* **2019**, *56*, 1449–1461. [CrossRef]
24. Sànchez, A.H.; Soares, T.; Wolahan, A. Reliability Aspects of Mega-Constellation Satellites and Their Impact on the Space Debris Environmant. In Proceedings of the 2017 Annual Reliability and Maintainability Symposium (RAMS), Orlando, FL, USA, 23–26 January 2017; pp. 1–5.
25. De Weck, O.; de Neufville, R.; Staged, M.C. Deployment of Communications Satellite Constellations in Low Earth Orbit. *J. Aerosp. Comput. Inf. Commun.* **2004**, *1*, 119–136. [CrossRef]
26. McGrath, C.; Kerr, E.; Macdonald, M. An Analytical, Low-Cost Deployment Strategy for Satellite Constellations. In Proceedings of the 13th Reinventing Space Conference, Oxford, UK, 10–13 November 2015.
27. Crisp, N.; Smith, K.; Hollingsworth, P. Launch and deployment of distributed small satellite systems. *Acta Astronaut.* **2015**, *114*, 65–78. [CrossRef]
28. Lee, H.W.; Jakob, P.C.; Ho, K.; Shimizu, S.; Yoshikawa, S. Optimization of satellite constellation deployment strategy considering uncertain areas of interest. *Acta Astronaut.* **2018**, *153*, 213–228. [CrossRef]
29. Mitra, R.N.; Agrawal, D.P. 5G mobile technology: A survey. *ICT Express* **2015**, *1*, 132–137. [CrossRef]

30. Iera, A.; Molinaro, A. Designing the Interworking of Terrestrial and Satellite IP-Based Network. *IEEE Commun. Mag.* **2002**, *40*, 136–144. [CrossRef]
31. Chini, P.; Giambene, G.; Kota, S. A survey on mobile satellite systems. *Int. J. Satell. Commun. Netw.* **2009**, *28*, 29–57. [CrossRef]
32. Kodheli, O.; Gannoti, A.; Vanelli-Coralli, A. Integration of Satellites in 5G through LEO Constellations. In Proceedings of the Globecomm 2017–2017 IEEE Global Communications Conference, Singapore, 4–8 December 2017; pp. 1–6.
33. Pan, C.; Du, H.; Liu, Q. A Routing Algorithm for Mpls Traffic Engineering in Leo Satellite Constellation Network. *Int. J. Innov. Comput. Inf. Control.* **2013**, *9*, 4139–4149.
34. quantumCMD, Affordable C2 for Small Satellites. Available online: https://www.kratosdefense.com/products/space/satellites/command-and-control/quantumcmd (accessed on 31 August 2020).
35. Höyhtyä, M.; Mämmelä, A.; Chen, X.; Hulkkonen, A.; Janhunen, J.; Dunat, J.-C.; Gardey, J. Database-Assisted Spectrum Sharing in Satellite Communications: A Survey. *IEEE Access* **2017**, *5*, 25322–25341. [CrossRef]
36. Israel, D.; Edwards, B.L.; Staren, J.W. Laser Communications Relay Demonstration (LCRD) update and the path towards optical relay operations. In Proceedings of the 2017 IEEE Aerospace Conference, Yellowstone Conference Center, Big Sky, MT, USA, 4−11 March 2017; pp. 1–6.
37. Müncheberg, S.; Gal, C.; Horwath, J.; Kinter, H.; Navajas, L.M.; Soutullo, M. Development status and breadboard results of a laser communication terminal for large LEO constellations. In Proceedings of the SPIE 11180, International Conference on Space Optics—ICSO 2018, Palatanias, Greece, 9−12 October 2018.
38. Nag, S.; Murakami, D.; Marker, N.; Lifson, M.; Kopardekar, P. Prototyping Operational Autonomy for Space Traffic Management. In Proceedings of the 70th International Astronautical Congress (IAC), Washington, DC, USA, 21−25 October 2019; p. 16.
39. Morton, M.; Roberts, T. Joint space operations center (JSpOC) mission system (JMS). In Proceedings of the 2011 AMOS Conference, Maui, HI, USA, 13−16 September 2011; p. 9.
40. Diserens, S.; Lewis, H.G.; Fliege, J. IAC-19-A6.2.6: NewSpace and its implications for space debris models. *J. Space Saf. Eng.* **2020**, 9. [CrossRef]
41. Anz-Meador, P.D.; Phillip, D.; Opiela, J.N.; Shoots, D.; Liou, J.-C. *History of On-Orbitsatellite Fragmentations*, 15th ed.; NASA Technical Reports; National Aeronautics and Space Administration, Lyndon B. Johnson Space Center: Huston, TX, USA, 4 July 2018; pp. 1–637.
42. Bonnal, C.; Ruault, J.-M.; Desjean, M.-C. Active debris removal: Recent progress and current trends. *Acta Astronaut.* **2013**, *85*, 51–60. [CrossRef]
43. Felicetti, L.; Emami, M.R. A multi-spacecraft formation approach to space debris surveillance. *Acta Astronaut.* **2016**, *127*, 491–504. [CrossRef]
44. Flohrer, T.; Krag, H.; Klinkrad, H.; Schildknecht, T. Feasibility of performing space surveillance tasks with a proposed space-based optical architecture. *Adv. Space Res.* **2011**, *47*, 1029–1042. [CrossRef]
45. Angel, F.-A.; Ou, M.; Khanh, P.; Steve, U. A review of space robotics technologies for on-orbit servicing. *Prog. Aerosp. Sci.* **2014**, *68*, 1–26.
46. Infantolino, G.M. Application of Support. Vector Machines to Solar Generator Fault Detection and Space Traffic Management. Available online: https://www.politesi.polimi.it/handle/10589/140367# (accessed on 14 April 2020).
47. Infantolino, G.M.; di Lizia, P.; Topputo, F.; Bernelli-Zazzera, F. On-Board Telemetry Monitoring via Support Vector Machine with Application to Philae Solar Generator. *Aerotec. Missili E Spaz.* **2018**, *97*, 183–188. [CrossRef]
48. Bennett, J.C.S.; Lachut, M.; Kooymans, D.; Pollard, A.; Smith, C.; Flegel, S.; Möckel, M.; O'Leary, J.; Samuel, R.; Wardman, J.; et al. An Australian Conjunction Assessment Service. In Proceedings of the 2019 AMOS Conference, Maui, HI, USA, 17–20 September 2019; p. 9.
49. De Selding, P.B. Globalstar's 2nd-generation System Slated to Begin Launching This Fall. 29 January 2010. Available online: https://spacenews.com/globalstars-2nd-generation-system-slated-begin-launching-fall/ (accessed on 2 July 2019).
50. Hassin, J.B.; Iridium, L.K. Completes Historic Satellite Launch Campaign. 11 January 2019. Available online: http://investor.iridium.com/2019-01-11-Iridium-Completes-Historic-Satellite-Launch-Campaign (accessed on 2 July 2019).

51. Caleb, H. OneWeb Files for Chapter 11 bankruptcy. 27 March 2020. Available online: https://spacenews.com/oneweb-files-for-chapter-11-bankruptcy/ (accessed on 14 April 2020).
52. Caleb, H. SES Building a 10-terabit O3b 'mPower' Constellation. 11 September 2017. Available online: https://spacenews.com/ses-building-a-10-terabit-o3b-mpower-constellation/ (accessed on 3 July 2019).
53. Rochelle, P. ORBCOMM Announces Commercial Service for Its Final 11 OG2 Satellites. 1 March 2016. Available online: https://www.orbcomm.com/en/company-investors/news/2016/orbcomm-announces-commercial-service-for-its-final-11-og2-satellites (accessed on 28 July 2019).
54. Our mission is Space Communication. Available online: http://www.gonets.ru/eng/company/mission/ (accessed on 3 July 2019).
55. Keane, P. SpaceX Starlink Constellation. 9 November 2018. Available online: https://www.engineering.com/AdvancedManufacturing/ArticleID/17928/SpaceX-Starlink-Constellation.aspx (accessed on 3 July 2019).
56. Caleb, H. Telesat Says Ideal LEO Constellation is 292 Satellites, But Could Be 512. 11 September 2018. Available online: https://spacenews.com/telesat-says-ideal-leo-constellation-is-292-satellites-but-could-be-512/ (accessed on 28 July 2019).
57. BlackSky, S.E. Secures $50 Million Financing from Intelsat. 12 November 2019. Available online: https://spacenews.com/blacksky-secures-50-million-financing-from-intelsat/ (accessed on 14 April 2020).
58. Lemur-2 Nanosatellite Constellation of Spire Global. Available online: https://directory.eoportal.org/web/eoportal/satellite-missions/l/lemur#foot6%29 (accessed on 3 July 2019).
59. Zimmerman, R.; Doan, D.; Leung, L.; Mason, J.; Parsons, N.; Shaid, K. Commissioning the world's Largest Satellite Constellation. In Proceedings of the 31st Annual AIAA/USU Conference on small Satellites, Logan, UT, USA, 5–10 August 2017.
60. Safyan, M. When Doves Fly: 48 Flock 2k Satellites Successfully Launched and Deployed. 14 July 2017. Available online: https://www.planet.com/pulse/when-doves-fly-48-flock-2k-satellites-successfully-launched-and-deployed/ (accessed on 3 July 2019).
61. SkySat constellation of Terra Bella—Formerly SkySat Imaging Program of Skybox Imaging. Available online: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/skysat-constellation-of-terra-bella-formerly-skysat-imaging-program-of-skybox-imagi-5 (accessed on 3 July 2019).
62. Caleb, H. Kepler Communications Opens Launch Bids for Gen-1 LEO Constellation. 29 August 2018. Available online: https://spacenews.com/kepler-communications-opens-launch-bids-for-gen-1-leo-constellation/ (accessed on 3 July 2019).
63. Kinéis Raises 100 Million Euros and Finances its Constellation of Nanosatellites Dedicated to the Internet of Things (IoT). 3 February 2020. Available online: https://www.kineis.com/en/kineis-raises-100-million-euros-and-finances-its-constellation-of-nanosatellites-dedicated-to-the-internet-of-things-iot (accessed on 14 April 2020).
64. exactView™ Constellation. 2019. Available online: https://www.exactearth.com/technology/exactview-constellation (accessed on 3 July 2019).
65. Schingler, R. Planet Launches Satellite Constellation to Image the Whole Planet Daily. 14 February 2017. Available online: https://www.planet.com/pulse/planet-launches-satellite-constellation-to-image-the-whole-planet-daily/ (accessed on 3 July 2019).
66. Safyan, M. First Up for 2019: PSLV Launch of 20 Next-Generation Doves. 6 March 2019. Available online: https://www.planet.com/pulse/first-up-for-2019-pslv-launch-of-20-next-generation-doves/ (accessed on 3 July 2019).
67. Systems. 2018. Available online: https://www.astrodigital.com/systems (accessed on 3 July 2019).
68. Weiss, W.; Rucinski, S.; Moffat, A.; Schwarzenberg-Czerny, A.; Koudelka, O.; Grant, C.; Zee, R.; Kuschnig, R.; Matthews, J.; Orleanski, P.; et al. BRITE-Constellation: Nanosatellites for Precision Photometry of Bright Stars. *Publ. Astron. Soc. Pac.* **2014**, *126*, 573–585. [CrossRef]
69. GHGSAT-C1/C2. 2019. Available online: https://www.ghgsat.com/who-we-are/our-satellites/satellite-2/ (accessed on 4 July 2019).
70. Foust, J. Satellogic Selects China Great Wall to Launch Satellite Constellation. 15 January 2019. Available online: https://spacenews.com/satellogic-selects-china-great-wall-to-launch-satellite-constellation/ (accessed on 14 April 2020).
71. Foust, J. Chinese Satellites Raising Orbits after Launch Anomaly. 30 December 2016. Available online: https://spacenews.com/chinese-satellites-raising-orbits-after-launch-anomaly/ (accessed on 4 July 2019).

72. China to Develop 300-Satellite Constellation. 1 March 2018. Available online: https://www.aerospace-technology.com/news/china-to-develop-300-satellite-constellation/ (accessed on 4 July 2019).
73. Hanry, C. LeoSat, Absent Investors, Shuts Down. November 2019. Available online: https://spacenews.com/leosat-absent-investors-shuts-down/ (accessed on 14 April 2020).
74. Wendell, R. Satellite Company SAS Global Joins Rush to Boost Africa Connectivity. 15 November 2018. Available online: https://telecom.economictimes.indiatimes.com/news/satellite-company-sas-global-joins-rush-to-boost-africa-connectivity/66634260 (accessed on 4 July 2019).
75. Science. Available online: http://www.geooptics.com/science/ (accessed on 4 July 2019).
76. Fulford, J.; Chu, V.; Liu, T.-Y.; Yen, N.; Wang, Y.-H.; Hsueh, C.-W.; Yang, C.-L. FORMOSAT-7/COSMIC-2 Mission Is Nearing Launch. 10 March 2016. Available online: https://www.nspo.narl.org.tw/ICGPSRO2016/download/S07-01_FS7C2%20Mission%20is%20Nearing%20Launch_NSPO%20NOAA.pdf (accessed on 4 July 2019).
77. PlanetiQ. 2019. Available online: http://planetiq.com/ (accessed on 4 July 2019).
78. Jiang, Y.; Jingyin, W.; Zhang, G.; Li, X.; Wu, J. Geometric Processing and Accuracy Verification of Zhuhai-1 Hyperspectral Satellites. *Remote Sens.* **2019**, *11*, 996. [CrossRef]
79. Mahoney, D. Canon Launching Imaging Satellites, Discusses 100+ Satellite Constellation. 12 June 2018. Available online: https://www.spaceitbridge.com/canon-launching-imaging-satellites-discusses-100-satellite-constellation.htm (accessed on 4 July 2019).
80. Wood, T. Helios Wire Satellite Scheduled to Launch on Spaceflight's SSO-A Smallsat Express Mission. 16 November 2018. Available online: https://helioswire.com/helios-wire-satellite-scheduled-launch-spaceflights-sso-smallsat-express-mission/ (accessed on 4 July 2019).
81. Spangelo, S. Introducing Swarm: The World's Lowest-Cost Global Communications Network. 30 August 2018. Available online: https://medium.com/swarm-technologies/introducing-swarm-549b804f1fa1 (accessed on 4 July 2019).
82. Sheetz, M. Finnish Startup ICEYE Is Building the World's Largest Constellation of Tiny Satellites to See through Clouds. 4 June 2018. Available online: https://www.cnbc.com/2018/06/01/iceye-building-worlds-largest-sar-constellation-with-microsatellites.html (accessed on 4 July 2019).
83. Unlock the Power of Data from Space. 2019. Available online: https://www.analyticalspace.com/ (accessed on 4 July 2019).
84. Corner, S. Nanosatellite Hopefuls Eyeing IoT Opportunities. 1 March 2019. Available online: https://www.zdnet.com/article/nanosatellite-hopefuls-eyeing-iot-opportunities/ (accessed on 4 July 2019).
85. Spence, A. Fleet Space Technologies Raising Funds for Constellation of Nano-Satellites. 14 July 2017. Available online: https://newsleads.com.au/investing/2017/07/14/fleet-space-technologies-raising-funds-for-constellation-of-nano-satellites/ (accessed on 4 July 2019).
86. Space Connected. 2019. Available online: https://audacy.space/ (accessed on 4 July 2019).
87. Faust, J. ELSE Raises $3 Million for Internet of Things Nanosatellite Constellation. 10 August 2017. Available online: https://spacenews.com/else-raises-3-million-for-internet-of-things-nanosatellite-constellation/ (accessed on 5 July 2019).
88. Our Fleet. 2019. Available online: http://aistechspace.com/fleet (accessed on 5 July 2019).
89. Sarda, K.; Roth, N.; Zee, R.; CaJacob, D.; Nathan, G.O. Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission. In Proceedings of the 4S Symposium, Sorrento, Italy, 28 May–1 June 2018.
90. Sensing the World, Changing the Future. Available online: https://www.axelspace.com/en/axelglobe_/ (accessed on 5 July 2019).
91. Technology. Available online: https://www.capellaspace.com/technology/ (accessed on 5 July 2019).
92. Karten Space Nanosatellites. Available online: https://kartenspace.com/nanosatellites/ (accessed on 5 July 2019).
93. Space is magic. 2018. Available online: https://unseenlabs.space/ (accessed on 5 July 2019).
94. New Satellite Technology from from SkyFi Enables Worldwide Internet Access Anywhere, Anytime. 3 August 2017. Available online: https://www.nslcomm.com/single-post/2017/08/03/New-Satellite-Technology-from-from-SkyFi-Enables-Worldwide-Internet-Access-Anywhere-Anytime#! (accessed on 5 July 2019).

95. Van Wagenen, J. EightyLEO IoT Constellation Hones Architecture, Name and Focus. 11 January 2017. Available online: https://www.satellitetoday.com/telecom/2017/01/11/eightyleo-iot-constellation-hones-architecture-name-focus/ (accessed on 5 July 2019).
96. Urthecast Corp Satellite Imaging. Geoanalytics. Insights. Available online: https://www.urthecast.com/ (accessed on 14 April 2020).
97. Premium Weather Data Captured by State-of-the-Art Satellite Technology. Available online: https://www.orbitalmicro.com/ (accessed on 5 July 2019).
98. Karaliunaite, V. Lacuna Space Has Contracted NanoAvionics to Integrate and Launch Its IoT Communications System On-Board of the M6P Nano-Satellite Bus. 24 April 2018. Available online: https://n-avionics.com/nanoavionics-lacuna-space-launch-contract/ (accessed on 5 July 2019).
99. About. Available online: https://www.herasys.com/ (accessed on 5 July 2019).
100. Hongyan, Y.L. Satellite Constellation to be Operating by 2025. 19 September 2018. Available online: http://www.ecns.cn/news/sci-tech/2018-09-19/detail-ifyyehna1446014.shtml (accessed on 5 July 2019).
101. Russell, K. SRT Marine to Build and Launch Satellite Constellation. 25 September 2017. Available online: https://www.satellitetoday.com/innovation/2017/09/25/srt-marine-build-launch-satellite-constellation (accessed on 5 July 2019).
102. Real-Time Earth-Observation Constellation. 2019. Available online: https://satrevolution.com/rec/ (accessed on 5 July 2019).
103. China to Launch Constellation with 72 Satellites for Internet of Things. 3 July 2019. Available online: http://www.chinadaily.com.cn/a/201907/03/WS5d1c543ea3105895c2e7b71d.html (accessed on 5 July 2019).
104. Aerial and Maritime Ltd. to Scale up ADS-B Data Nanosatellite Network—Secures Additional 5.0 Million USD Funding. 16 November 2017. Available online: http://aerial-maritime.com/GB/News.aspx (accessed on 5 July 2019).
105. Glumb, R.; Lapsley, M.; Mantica, P.; Glumb, A. TRL6 Testing of Hyperspectral Fourier Transform Spectrometer Instrument for CubeSat Applications. In Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan, UT, USA, 5–10 August 2017.
106. The Vivid-i Constellation. 2019. Available online: https://earthi.space/constellations/ (accessed on 5 July 2019).
107. Nield, D. LinkSure is Building a Satellite Network to Provide Global Internet Access for free. 30 November 2018. Available online: https://newatlas.com/linksure-satellite-free-internet-network/57466/ (accessed on 5 July 2019).
108. Satellite. Available online: https://synspective.com/satellite/ (accessed on 5 July 2019).
109. ÅAC Microtec wins a Binding order from Space Systems Engineering Ukraine for Avionics and Power Subsystems. 31 May 2018. Available online: http://investor.aacmicrotec.com/pressmeddelanden/aac-microtec-wins-a-binding-order-from-space-systems-enginee-65682 (accessed on 5 July 2019).
110. We are Astrome. 2019. Available online: http://www.astrome.co/about-us-page/ (accessed on 14 April 2020).
111. News and Company Highlights. 9 April 2019. Available online: http://swissdevco.com/news/spacebelt/ (accessed on 12 July 2019).
112. Superfast Global Internet. 2018. Available online: https://transcelestial.com/ (accessed on 12 July 2019).
113. Data Products. 2019. Available online: https://kleos.space/products/ (accessed on 12 July 2019).
114. Hipersat—Press Releases. 14 September 2018. Available online: https://www.hypersat.com/ (accessed on 12 July 2019).
115. Make The Earth Better. Available online: http://www.yinhe.ht/indexEn.html (accessed on 12 July 2019).
116. Lei, Z. Hainan Eyes New Satellite Network. 16 August 2018. Available online: http://english.gov.cn/news/top_news/2018/08/16/content_281476263529908.htm (accessed on 12 July 2019).
117. Program Objectives. 2019. Available online: http://www.lf.link/program-objectives (accessed on 12 July 2019).
118. About. 2018. Available online: http://www.xpresssar.com/about/#about-xsar (accessed on 14 April 2020).
119. Orbital ORacle Technologies (orora.tech): Advanced Cubesat Constellation for Global Near Real-Time Weather Forecasting. 27 September 2018. Available online: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/TTP2/Orbital_Oracle_Technologies_orora.tech_Advanced_CubeSat_Constellation_for_Global_near_real-time_Weather_Forecasting (accessed on 12 July 2019).
120. Our Vision. 2019. Available online: https://www.metheraglobal.com/ (accessed on 12 July 2019).

121. Erwin, S. Trident Space's Challenge: Standing out from the Crowd of SAR Satellite Startups. 22 August 2018. Available online: https://www.metheraglobal.com/ (accessed on 12 July 2019).
122. Veoware Space Satellite Imagery Services: Get the Right Satellite Image at the Right Moment. 10 September 2018. Available online: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/TTP2/Veoware_Space_satellite_imagery_services_get_the_right_satellite_image_at_the_right_moment (accessed on 12 July 2019).
123. Services. Available online: https://umbralab.com/services/ (accessed on 12 July 2019).
124. Caleb, H. Startup with SoftBank, Airbus Investment Planning Video Constellation with Several Hundred Satellites. 18 April 2018. Available online: https://spacenews.com/startup-with-softbank-airbus-investment-planning-video-constellation-with-several-hundred-satellites/ (accessed on 12 July 2019).
125. Our Technology. 2019. Available online: http://www.oqtec.space/#technology (accessed on 12 July 2019).
126. Caleb, H. Portuguese Company Embarks on First Domestic Satellite Project. 10 November 2017. Available online: https://spacenews.com/portuguese-company-embarks-on-first-domestic-satellite-project/ (accessed on 12 July 2019).
127. Constellation. Available online: https://kleo-connect.com/constellation (accessed on 13 July 2019).
128. Caleb, H. LEO startup raises $39.5 million for constellation to watch Earth and space. 16 November 2018. Available online: https://spacenews.com/leo-startup-raises-39-5-million-for-constellation-to-watch-earth-and-space/ (accessed on 13 July 2019).
129. About Us. 2018. Available online: https://www.laserlightcomms.com/ (accessed on 13 July 2019).
130. Your Swiss Army Knife for Responding to Your Environment. Available online: http://koolock.com/tech.html (accessed on 13 July 2019).
131. Zak, A. Russia to Build Arctic Satellite Network. 6 October 2018. Available online: http://www.russianspaceweb.com/arktika.html (accessed on 13 July 2019).
132. Home. Available online: http://www.hypercubes.global/ (accessed on 13 July 2019).
133. Russia to Create Orbital Internet Satellite Cluster by 2025. 22 May 2018. Available online: https://tass.com/science/1005554 (accessed on 13 July 2019).
134. Mann, A. B612 plans asteroid hunt with fleet of small satellites. *Science* **2018**, *360*, 842–843. [CrossRef] [PubMed]
135. Atkinson, J. NASA's CYGNSS Satellite Constellation Begins Public Data Release. 24 May 2017. Available online: https://www.nasa.gov/feature/nasa-s-cygnss-satellite-constellation-begins-public-data-release (accessed on 13 July 2019).
136. About Us. 2018. Available online: https://www.cgsatellite.com/about-us/ (accessed on 13 July 2019).
137. Jeff, F. OmniEarth acquired by EagleView, Continuing Satellite-Imagery Consolidation Wave. 28 April 2017. Available online: https://spacenews.com/omniearth-acquired-by-eagleview/ (accessed on 28 July 2019).
138. The Constellation. 2013. Available online: http://www.commstellation.com/constellation/index.html (accessed on 28 July 2019).
139. Myriota Moves One Step Closer to Nanosat Constellation. 15 February 2019. Available online: https://www.australiandefence.com.au/defence/cyber-space/myriota-moves-one-step-closer-to-nanosat-constellation (accessed on 5 August 2019).
140. Wang, Y. ADASpace Set to Star in AI Satellite Constellation Sphere. 30 June 2019. Available online: http://www.globaltimes.cn/content/1156263.shtml (accessed on 5 August 2019).
141. Cell Towers in Space. 2019. Available online: https://www.ubiquitilink.com/our-technology (accessed on 14 April 2020).
142. Megapie Constellation: Small Sat Great Dream. 2017. Available online: http://en-online.cubesatgarage.com/special/index#section-1 (accessed on 5 August 2019).
143. Space Data Made Easy. 2019. Available online: https://www.stara.space/ (accessed on 5 August 2019).
144. Hyperion: SPACE SITUATIONAL AWARENESS. 2018. Available online: https://www.inovor.com.au/space-technology/hyperion-mission/ (accessed on 5 August 2019).
145. T. Withington All at Sea: The Growing Provision of Private-Sector Signals Intelligence Gathering Will Take an Important Step Forward with the Launch of the UK's IOD-3 AMBER CubeSat in 2020. 17 May 2019. Available online: https://chainhomehigh.com/category/horizon-technologies/ (accessed on 5 August 2019).
146. SpaceFab.US Awards Space Telescope Time for Research. 4 January 2019. Available online: http://www.spacefab.us/updatesnews (accessed on 5 August 2019).

147. HEO Robotics Engages in Space Demonstration with Royal Australian Air Force. 11 March 2019. Available online: https://www.heo-robotics.com/post/heo-robotics-engages-in-paid-demonstration-with-royal-australian-air-force (accessed on 5 August 2019).
148. BEACON IoT Constellation. Available online: http://www.spaceartemis.com/beacon-iot-constellation/ (accessed on 5 August 2019).
149. The Master Plan. Available online: https://pixxel.co.in/ (accessed on 5 August 2019).
150. Space Segment. Available online: https://www.gps.gov/systems/gps/space/ (accessed on 27 August 2020).
151. Polischuk, G.M.; Kozlov, V.; Ilitchov, V.; Kozlov, A.G.; Bartenev, V.A.; Kossenko, V.; Anphimov, N.; Revnivykh, S.; Pisarev, S.; Tyulyakov, A.; et al. The Global Navigation Satellite System Glonass: Development and Usage in the 21st Century. In Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Meeting, Reston, VA, USA, 3–5 December 2002; p. 11.
152. Galileo Factsheet. Available online: http://download.esa.int/docs/Galileo_IOV_Launch/Galileo_factsheet_2012.pdf (accessed on 27 August 2020).
153. China Puts Final Satellite for Beidou Network into Orbit. Available online: https://financialpost.com/pmn/business-pmn/china-puts-final-satellite-for-beidou-network-into-orbit-state-media (accessed on 27 August 2020).