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Satellite Constellations - 2021 Industry Survey and Trends

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ABSTRACT

Large satellite constellations are becoming reality. Starlink has launched over 1600 spacecraft in 2 years since the launch of the first batch, Planet has launched over 450, OneWeb more than 200, and counting. Every month new constellation projects are announced, some for novel applications.

First part of the paper focuses on the industry survey of 251 commercial satellite constellations. Statistical overview of applications, form factors, statuses, manufacturers, founding years is presented including early stage and cancelled projects. Large number of commercial entities have launched at least one demonstrator satellite, but operational constellations have been much slower to follow. One reason could be that funding is commonly raised in stages and the sustainability of most business models remains to be proven.

Second half of the paper examines constellations by selected applications and discusses trends in applications, satellite masses, orbits and manufacturers over the past 5 years. Earliest applications challenged by NewSpace were AIS, Earth Observation, Internet of Things (IoT) and Broadband Internet. Recent years have seen diversification into majority of applications that have been planned or performed by governmental or military satellites, and beyond.

INTRODUCTION

NewSpace Index has tracked commercial satellite constellations since 2016. There are over 251 entries as of May 2021, which likely makes it the largest public database. The initial target was nanosatellites, but scope was expanded to all satellites when a large quantity of small satellite constellations started to be announced. For comparison, there were only 60 projects listed at the end of 2017.

Literature review was performed and surveys about constellations seem to be relatively sparse. Seraphim has published a Constellation Map[1] along with many similar market maps from other entities. One paper surveyed 90 missions and had basic statistics.[2] Selected papers have focused on Earth Observation[3] or telecommunications.[4–6]

First Wave of Commercial Constellations

Around 15 commercial LEO constellations for communications (broadband, messaging and voice) were announced in the late 1980s and during the 1990s.[7–11] Most of them had failed by the early 2000s including Teledesic. While Orbcomm, Iridium and Globalstar were successful in launching their first-generation constellations, they also went bankrupt and were restructured by the early 2000s. Commercial geostationary communications satellites have been launched since 1960s (Telstar, Intelsat), but they are regarded to be fleets not constellations.

There were much fewer Earth Observation companies in 1990s and 2000s when compared to communications and unclear whether any large constellations were planned. 1992 Land Remote Sensing Policy Act allowed U.S. commercial companies to enter the satellite imagery business.[12,13] DigitalGlobe (WorldView, EarthWatch)[12] and Orbimage (GeoEye)[13] were founded in 1992 and were followed by Space Imaging in 1994.[14] First commercial EO satellite launches were in 1997, EarlyBird-1 for DigitalGlobe and Orbivew-2 for Orbimage. The first high-resolution commercial EO satellite IKONOS from Space Imaging launched in 1999. French Space Agency established subsidiary Spot Imaging to sell commercial imagery in 1982.[15] Israel's ImageSat launched EROS-A in 2000 and planned a 4-satellite constellation, but it was cancelled.[16]

Current Second Wave of Constellations

After the failures of satellite communications companies, commercial Earth Observation satellites continued to be launched about one every 2-3 years. The market saw consolidation, because Orbimage acquired Space Imaging in 2006 to form GeoEye and DigitalGlobe bought GeoEye in 2013.[17]

Earliest entries in the database are AprizeSat and SaudiComsat with the first launches in 2002 and 2004, respectively. ExactEarth started its constella-

tion in 2008 and some payloads were hosted aboard AprizeSat. These were all smaller microsatellites with a mass of about 12 kg and offered Internet of Things (IoT) and Machine-to-Machine (M2M) communication services or AIS message collection.

RapidEye was created in 1998, announced financing in 2004 and launched 5 spacecraft in 2008.[18] It entered bankruptcy in 2011 and was sold when sales of $18 million were not strong enough to pay back debts.[19] Planet was founded in 2010 as Cosmogia, launched 3U CubeSats in 2013 and the first batch of 28 in early 2014.[20] Skybox, founded in 2009, was inspired by CubeSats,[21] raised $91 million by April 2012,[22] launched spacecraft in 2013,[23] was bought by Google for $500 million in 2014 (renamed Terra Bella) and sold to Planet in early 2017.[24]

O3b (now SES) was founded in 2007 and launched first 4 MEO satellites in 2013.[25] Orbcomm, Iridium and Globalstar developed second-generation constellations. After finishing OG-1 in 1999, Orbcomm followed with replenishments in 2008 and launched OG-2 in 2014 and 2015.[26] Iridium contracted for the NEXT constellation in 2010 and launches were between 2017-2019.[27] Globalstar launched replenishments in 2007 and next generation from 2010 to 2013.[28]

News articles and speculations about OneWeb and SpaceX constellations appeared throughout 2014.[29–31] OneWeb (WorldVu) was founded in 2012 and was publicly announced in 2015[32] as well as Starlink in early 2015.[33] OneWeb entered bankruptcy in 2020, was bought and has continued with satellite deployments.[34] LeoSat was founded in 2013, raised over $10 million and shut down in 2019 after failing to attract further funding.[35]

First CubeSats started launching in 2003, popularity started to increase around 2008 and launches really took off in 2013, coinciding with the constellations from Planet and Spire. This partially correlates with an increase in constellation companies from 2009 and with the jump in 2015 as seen on Figure 7. "The CubeSat Orbcomm" was proposed in 2010. Sky and Space went public in 2016 and partially kicked off the IoT/M2M field popularity.

ITU first received half a dozen filings for large constellations in late 2014 and early 2015.[36] Perhaps largely inspired by Planet, Spire, Skybox, OneWeb, SpaceX and by the general NewSpace prevalence.

Many constellations are raising more and more funding even when business models have not been proven. Latest trend is SPACs: Spire, BlackSky and Arqit with likely more upcoming. After the recent SEC rule changes, this approach might slow down.

MARKET SURVEY

Survey Criteria

- Satellite constellation - Number of similar satellites, of a similar type and function, designed to be in similar, complementary, orbits for a shared purpose, under shared control.[37] Sometimes defined as a set of satellites working together in order to provide a service or a group of satellites with a common purpose.[38,39] Different from satellite programs and fleets.
- 3 or more spacecraft - Minimum required for a continuous coverage in geostationary or Molniya orbits. Literature review revealed minimum satellite counts of 2^{40} and official definition has not been found, but 3 appropriately filters out many satellite pairs.
- Commercial focus - Primarily owned, financed and managed by commercial entities for the purpose of providing a commercial service. Excluding government, military, academic, scientific and non-profit constellations. Likely to be expanded in the future, because all constellations will have an impact to the space economy including launch and manufacturing services.
- Announced or launched after 2002 - Filtering out the first-generation constellations for Iridium, Globalstar and Orbcomm as of now, in addition to other projects from the 1990s.

Applications Classification

There are constellations with multiple applications, both by naming or the same satellite having different payloads. The following list of keywords, applications and fields is not exhaustive.

- Optical Earth Observation (EO) - VNIR (Visible and Near-Infrared), Multispectral - Earth Observation and remote sensing are very broad terms, but here defining optical EO as using passive silicon CCD or CMOS image sensors to collect imagery of Earth in visible and near-infra-red wavelengths.[41] Most multispectral instruments have 3 to 20 spectral bands and there is overlap with VNIR constellations.[42]
- Infrared EO - Divides into SWIR (Short-Wave Infrared), MWIR (Mid-Wave Infrared) and LWIR (Long-Wave Infrared) and often also known as thermal imaging. Commonly used for weather and climate monitoring, and for forest fire detection for example.[43]

- Hyperspectral EO - More than 20 spectral bands and typically hundreds of narrow spectral bands, which enables new applications in agriculture, vegetation, geology and water resources to identify specific organic matter.[44]
- SAR (Synthetic Aperture Radar) - Emits microwave radiation and collects the reflected radiation to form an image. Synthetic aperture is used to synthesize a long antenna by combining reflected signals as the satellite moves along orbit. Spaceborne radar satellites, for example in X, C or L radio bands, see through clouds and are not dependent on sunlight.[45,46]
- VR/AR (Virtual Reality, Augmented Reality) - Subset of EO with stereo or 360 degree cameras for 3D pictures and videos.
- Video - Subset of EO for high-resolution video capture and possibly real-time transmission.[47]
- Emissions Monitoring - Remote sensing, quantifying and locating greenhouse gas emissions, for example CO_2 and methane, using spaceborne imaging spectrometers.[48,49]
- Internet (Broadband) - Wideband high-speed satellite communications offering real-time Internet or data backhaul service.[50]
- IoT / M2M - Using satellites to extend the coverage of IoT (Internet of Things) and M2M (Machine-to-Machine) communications for remote areas. Often one-way or two-way messages and low data rates in narrowband.[51,52]
- Store-and-Forward - Subset of satellite communications, both narrowband and wideband, which is not real-time and data is stored on the spacecraft until a ground station pass.[53]
- 5G - Subset of satellite communications and IoT / M2M using 5G standards including NB-IoT, that may be compatible with common terrestrial equipment including smartphones.[54,55]
- Satellite-to-Cellphone - Subset of satellite communications, which is capable of sending and/or receiving text messages, voice calls or even real-time broadband data from unmodified mobile phones to spacecraft.[56]
- Laser Communications - Constellations capable of space-to-ground optical communications. Foreseen for downlink and uplink, but lasers are also used for inter-satellite links.[57,58]
- Orbital Data Relay (Internet in Space, Space Data Relay) - Providing telemetry & telecommand and ground station service to other satellites. Aim is to connect space assets to mission control centres in real-time and to increase the amount of downlinked data.[59]
- QKD (Quantum Key Distribution) - Satellite-based QKD uses laser communications between two users to produce a common random secret key at a distance, which is then used to encrypt messages sent over a standard communication channel. Any eavesdropper on the quantum channel will introduce disturbance to the system that is in superposition state, which can then be detected by the two users.[60,61]
- ADS-B (Automatic Dependent Surveillance–Broadcast) - Every aircraft transmits its identification, position, altitude, speed and other information, which is relayed to air traffic controls for more accurate situational awareness.[62] Space-based ADS-B is used for tracking aircraft beyond the reach of land-based receivers, but it could be expanded to space-based air traffic services to provide more information to pilots.[63]
- AIS (Automatic Identification System) - Space-based AIS is used to track ships beyond the reach of land-based receivers by listening to the VHF radio transmissions of ships identity, position, speed and heading.[64]
- VDES (VHF Data Exchange System) - In some ways the next generation of AIS, which is starting to enter operation as of 2021. VDES encompasses AIS and adds a higher rate two-way data communications system, which also foresees a special satellite link. At the same time, new dedicated channels will solve AIS overloading problems in crowded waters.[65]
- Asteroid Prospecting - Mapping composition of asteroids for asteroid mining purposes. Here envisioned as rendezvous or flyby spacecraft for fine measurements, sometimes with MWIR sensors. Could be also asteroid discovery, characterization and cataloguing constellation in LEO to increase the known population.[66]
- On-Orbit Inspection - Satellites intended to maneuver nearby to other spacecraft for identification and to physically inspect deployables and malfunctions in case of problems.[67] Subfield of On-Orbit Satellite Servicing.
- In-Orbit Computing - Dedicated orbital servers for processing data from other satellites in space, before sending to ground or back to the satellites.[68,69] Can be related to In-Orbit Computing and Orbital Data Relay. Not

the same as orbital edge computing, which includes payload data processing boards and machine learning software.[70]

- In-Orbit Data Storage - Space-based cloud data storage service on-board satellites or inside laser beams, which could be highly secure when using narrow radio or laser beams. Could be related to In-Orbit Computing and Orbital Data Relay applications.[71]
- Constellation-As-A-Service - Full end-to-end service to build and operate a constellation for a customer. Sometimes called Satellite-Data-As-A-Service and can include payload development. Related to hosted payloads when sharing the same spacecraft. Many more commercial entities are offering or planning to offer this solution than shown in Figure 1.
- Hosted Payloads - Could be one-off or numerous in-orbit demonstration & verification missions for payloads and subsystems, or alternatively scientific or commercial microgravity experiments. Piggybacked on individual satellites or on another constellation.[72,73] Sometimes related to Constellation-As-A-Service and also called rent-a-satellite.
- GNSS (Global Navigation Satellite System) and PNT (Positioning, Navigation and Timing) - Commercial satellite navigation systems. Often envisioned to be based in LEO to provide better performance, much stronger signals, encryption and 3-D location when compared to free GPS, Galileo, GLONASS and BeiDou.[74,75] Possible that existing GNSS constellations signals will be used as inputs.[76]
- Orbital Display - Using formation flying satellites to compose a message or advertisement visible to the naked eye on Earth by using large deployable sails that reflect Sunlight.[77]
- RF Spectrum Monitoring and Geolocation - Listening for radio emissions with formation-flying spacecraft to identify and triangulate the sources. Common application is ships or vehicles that do not have AIS enabled.[78]
- Weather Monitoring - Measuring vertical atmosphere profiles of various parameters e.g. pressure, temperature, humidity and wind speed for weather and climate forecasting. Common technologies are GNSS-RO,[74] GNSS-R,[79] microwave radiometry and others.[80]
- Wireless Energy Supply - Providing satellites with extra electrical power from other spacecraft using microwave or laser power transmission.[81] Sub-field of Space-Based Solar Power.
- SSA (Space Situational Awareness) - Space-based SSA for detecting, monitoring and determining the orbits other satellites and space debris. To enable higher revisit and consecutive observations of objects.[82,83] Often performed with infra-red space telescopes, which could also be used for asteroid astronomy.
- Space Weather - Monitoring the effects of space weather to the ionosphere and magnetosphere by measuring energetic charged particles to help improve space weather forecasting models.[84,85] Satellites sometimes conceived to be located in Earth-Sun Lagrange-points to increase warning time for solar flares.[86]

Form Factors Classification

Constellations can consist of spacecraft with different masses and form factors. The database aims to capture and publicize all of the used or announced size classes. In this survey, only the latest known and most likely form factors for the majority of the satellites in a constellation have been presented for clarity. No official standard for mass definitions exists and the FAA mass classes[87] are too exhaustive so henceforth using the following reduced categories:

- PocketQubes (Femtosatellites) - Sizes from 1p to 3p, where 1p is $\approx$ 5 cm $\times$ 5 cm $\times$ 5 cm.[88]
- CubeSats (Nanosatellites) - Satellites following the CubeSat Design Specification from 0.25U to 16U, where 1U is 10 cm $\times$ 10 cm $\times$ 11.35 cm.[89] The general category is for constellations that will use CubeSats based on available information, but the exact type has not been made public.
- Hosted - Constellations hosting payloads on other multi-use satellites or constellations, where spacecraft resources are shared and spacecraft mass has lower correlation to the payload performance and specifications.
- Microsats - 10 kg to 100 kg, except larger CubeSats which can be up to 25 kg, because those masses are rarely shared publicly.
- Smallsats - 100 kg to 500 kg. Small satellites term is often used broadly for any satellite below 500 kg.
- Satellites - 500 kg and above.

Status Classification

Categories to indicate the current status of satellite constellations by consolidating various accessible information and in some cases an educated guess has been made:

- Launched - Constellation fully launched with no replenishments foreseen due to long expected lifetime and already existing orbital spares. Iridium is a fitting example.
- Launched and replenishing - Most of the planned constellation has been launched and the expected size has been achieved. New iterations are being sent to orbit every 1-3 years as satellites retire or deorbit. Planet and Spire fit well here.
- Launches ongoing - Constellation deployment of identical or similar satellites actively in progress or ramping up. Starlink and OneWeb are best examples.
- Prototype(s) launched - One or more first satellites or hosted payloads launched, which serve as prototypes or pathfinders.
- Prototype development - First payload or spacecraft is being actively worked on. Company seems to be growing and likely has announced one or more rounds of funding.
- Early stage / Concept - A few announcements, presentations and pitches for a constellation idea, but likely in the stages of starting development, looking for funding and gaining traction with a very small team.
- Dormant / Unknown - Early signs towards to the development has slowed down or stopped, but in rare cases can be explained with stealth mode or temporary setbacks.
- Cancelled - Company is bankrupt, website and social media channels have been quiet for more than 1-2 years, lack of funding announcements, team seems to have been disbanded and/or the idea never entered implementation phase.
- Retired - Constellation, which has been removed from active service, but satellites could still be in orbit and even operational.

Orbit Classification

ITU and FCC primarily differentiate non-geostationary (NGSO) and geostationary (GSO) orbits, but in the database large majority are NGSO.

- VLEO (Very Low Earth Orbit) - Here defined as sustained orbits with altitudes in the 250-350 km range.[90] Earth Observant's Stringray spacecraft will be designed to fly at 250 km altitude. Albedo Space[91] is expected to use similar orbit range. SpaceX V-band constellation between 336-346 km is also called VLEO.[92] Literature defines VLEO below 450-500 km altitude and Super Low Earth Orbit (SLEO) with perigee below 300 km, but both definitions seem to be rarely used in practice.[93]
- LEO (Low Earth Orbit) - Up to 2000 km from the Earth's surface, excluding the previous VLEO definition.
- MEO (Medium Earth Orbit) - Altitudes between 2000 km and 35786 km.
- GEO (Geosynchronous Earth Orbit) - Altitude of 35786 km.
- HEO (Highly Elliptical Orbit) - Low perigee (1000 km) and high apogee (35786 km). Includes Geostationary Transfer Orbit (GTO), Tundra orbit and Molniya orbit, where the latter two are special cases of Highly Inclined Elliptical Orbit (HIEO).
- Lunar - Constellations intended to orbit around the Moon. Sub-fields such as Low Lunar Orbit (LLO) will be created as applicable. Likewise with other Solar System bodies.

Delay Classification

Comparing launches and upcoming manifests to statements about launch cadences and deployment intentions. Plans change and not all delays should be taken as a bad sign, but nevertheless gives some indication about the company and industry.

- Cancelled - Cancelled and dormant constellations where no more launches are expected.
- Generally on-time - Up to 6 months of delays, some of which can be due to launch delays.
- Partially behind - Approximately 6-12 months of delays.
- Year behind - More than 1 year of delays.
- Years behind - More than 2-3 years of delays.
- Unknown - No public announcements found and unable to make a comparison.

2021 STATISTICAL OVERVIEW

Statistical overview of the 251 entries included in this commercial satellite constellations survey.

Applications and Fields

Many constellations perform multiple functions with identical or similar satellites. Figure 1 counts services independent of spacecraft multi-usage. In other words, applications and fields have been counted separately and the sum does not equal the number of entries in this survey. As seen on Figure 1, IoT / M2M is the most popular followed by Optical Earth Observation, Broadband Internet, SAR and AIS.

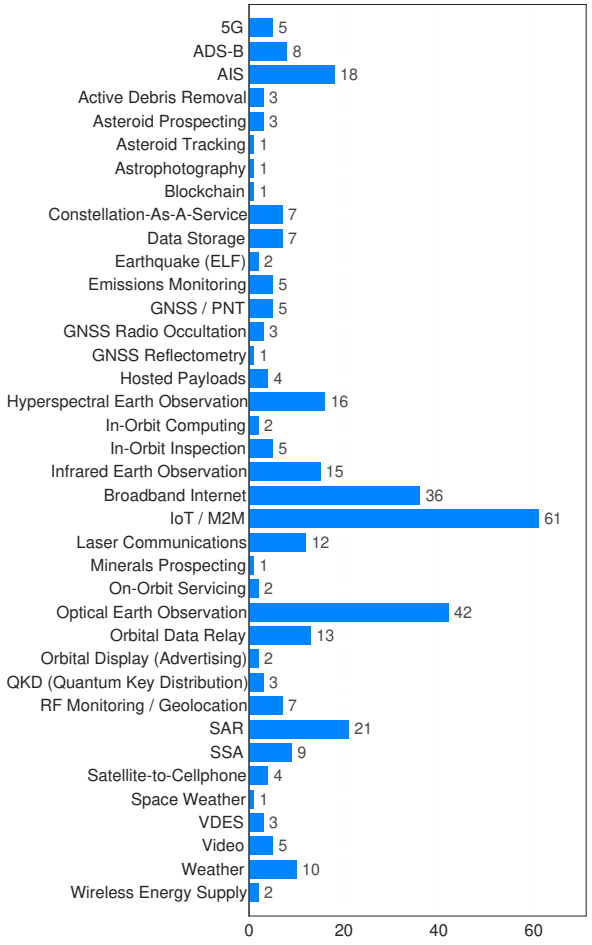

Figure 1: Constellations Applications

Current Status

Figure 2 shows the current activity and development status of the commercial constellations. Only about 4% are considered launched with 8% being actively launched. Approximately 20% have launched one or more prototypes while 29% are in development phase. About 25% have cancelled or dormant status and this could be larger. The one retired constellation is Planet's RapidEye.[19]

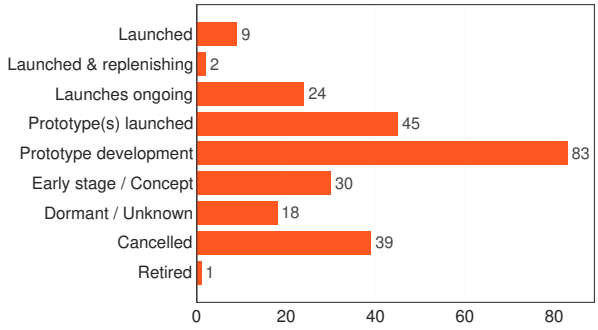

Figure 2: Constellations Current Status

Form Factors

The distribution of spacecraft size and type classes is visualized on Figure 3. CubeSats are the most popular segment with a combined 48%, including the 15% which are likely to be CubeSats, but specific form factor is currently unknown. Followed by microsatellites with 19% and small satellites with 14%. Mass classes for about 10% of the constellations have not been made public yet.

Among CubeSats, 3U continues to be the most popular thanks to Planet and Spire. Astro Digital's predecessors launched two 6U pathfinders in 2014. Sky and Space, GeoOptics and Kepler were developing and started launching 6U CubeSats to gain more capabilities. Kepler has 13 of 6U CubeSats in orbit, which is largest in that class. Many are now working with 12U-16U sizes. Swarm went into the opposite direction by using 0.25U CubeSats.

PocketQubes have been slower to become popular, but now Alba Orbital, Fossa Systems and others are developing constellations.

Some entities are moving towards larger microsatellites due to stacking, appendage, power and thermal limitations of CubeSats.

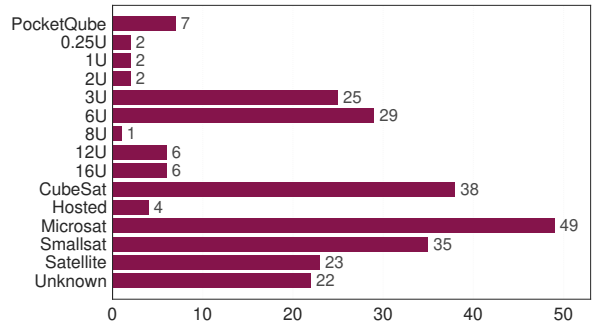

Figure 3: Constellation Form Factors

Manufacturers

Subcontracting the first or more spacecraft to a satellite manufacturer does not ensure a constellation order. Some have used the services of multiple integrators. Many have later switched to building the spacecraft in-house. The database lists multiple manufacturers when applicable, but in this survey only the latest used or announced satellite producer for a constellation has been presented on Figure 4.

About 37% are building spacecraft in-house and 33% of constellations are currently unknown. Rest divide between a large number of manufacturers. Few manufactures have full contracts and only a small number of constellations have been fully funded. Going further, it is likely that most constellations will not be continued or completed. Any manufacturer being awarded a large contract is a major success, when compared to demonstration missions.

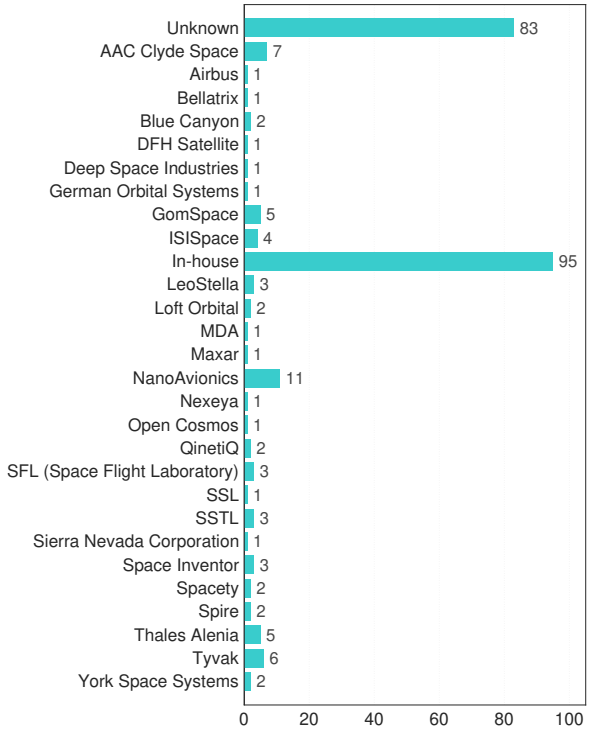

Figure 4: Constellation Subcontractors

Orbits

Figure 5 divides the NewSpace constellations by orbit types. LEO orbit is by far the most popular with 94% of 251. Recently, very-high resolution Earth Observation constellations in VLEO have been announced. MEO orbits are commonly used for Space Data Relay services. GEO orbit will see satellites primarily for In-Orbit Inspection and SSA.

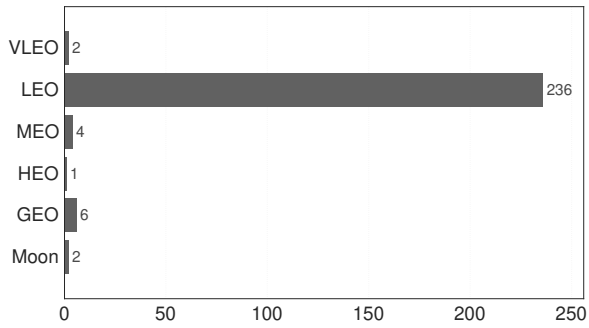

Figure 5: Constellation Orbits

Delays and Launch Cadences

Announced launch cadences were compared with the current launch status to create Figure 6. Most companies have not announced their plans and delays are very common. Only a small number are on-time and delayed less than 6-12 months from plans.

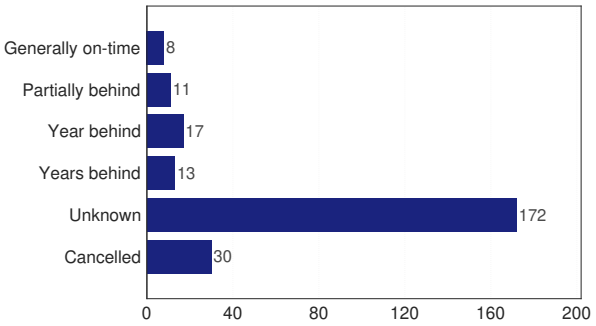

Figure 6: Constellation Delays

Companies Founded

Founding dates since 1991 are on Figure 7. Around 20 were left out with the earliest from 1895. There is a clear increase after 2009 with major peaks in 2015-2016. Decrease could be a sign of waiting to see how existing entities will perform economically.

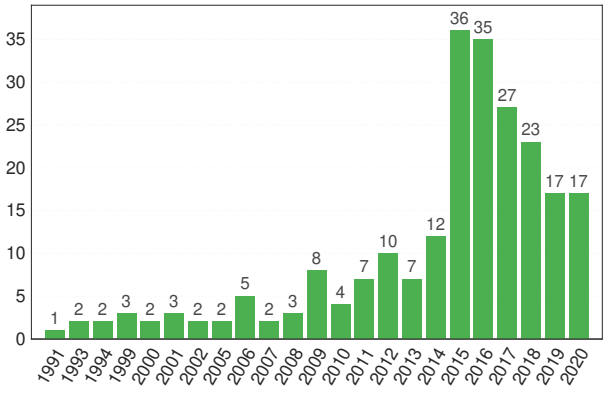

Figure 7: Constellation Companies Founded

Funding and Investments

Funding amounts, which have been made public, or estimated internal investments, have been summarised on Figure 8. Great quantity of companies have considerable funding. Capital does not always convert into results or the number of satellites. Many other entities have extensive investments based on activities, but the exact sums have not been announced. Approximately 17% have likely received no funding. Announced SPAC rounds will be added once the deals officially close.

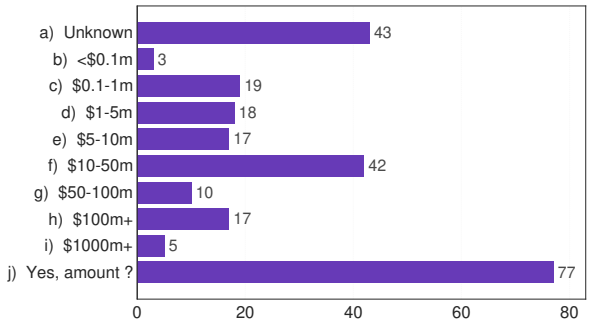

Figure 8: Constellations Funding

First Launches

First satellite launches of constellation companies are depicted on Figure 9. First launch is defined as the direct prototype or the first operational satellite of a constellation. In many cases, the form factor, payload, performance or even application of a pathfinder can be very different from the operational spacecraft. Peak can be seen between 2017-2019, which is about 2-3 years after the corresponding founding dates. 2020 saw the first operational batch launches for many constellations. Delays have been very common and will likely continue to be so.

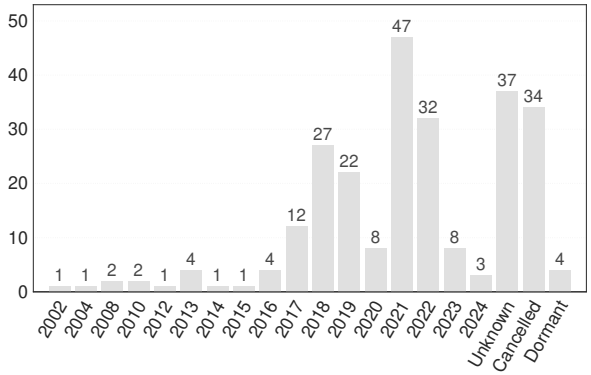

Figure 9: Constellation First Launches

World Map

Distribution of the constellation companies by headquarters locations is on Figure 10. The most notable case, where this does not match the manufacturing location, is Spire, whose satellites are assembled and tested in Glasgow, UK. Generally, the US is far ahead with 40% of constellations being located there, followed by China with 9%, UK with 7% and Canada with 5%. While Russia and India with domestic launch capability do not stand out among Spain, Italy and Australia for example.

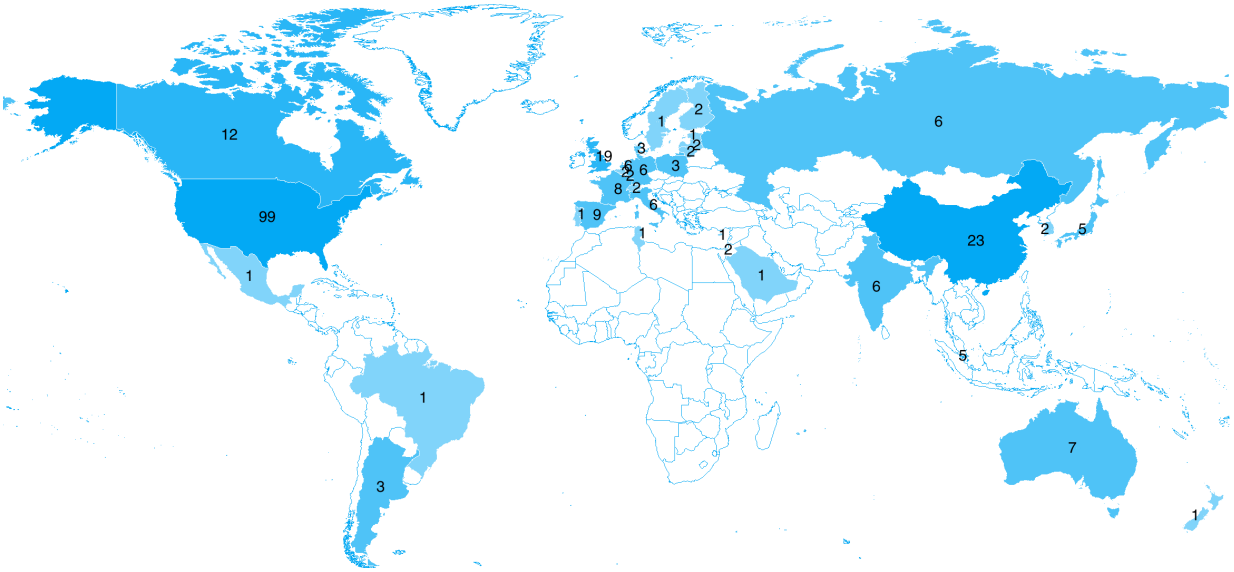

Figure 10: Constellations Headquarters Map

2021 SURVEY BY APPLICATIONS

This section presents commercial satellite constellations by selected applications in no specific order. Some trends discussions have been included. Each figure for an application includes the names of companies, status, launched and planned number of satellites. Prototypes are added to the launched count except in cases of established space companies. Not all are independent satellites, some are hosted payloads. Launch failures are included in the launched count, because the spacecraft were built and contracted to launch. The previously listed aspects are proof of activity and gives better insight.

Application: Optical EO (VNIR)

Figure 11 gathers Earth Observation constellations in the visible and near-infrared (VNIR) range and multispectral. Planet's Dove (SuperDove) and Skybox constellations together with BlackSky, Satellogic, Axelspace and Jilin-1 are being actively used and expanded. SatRevolution has multiple launches booked for 2021 and many others e.g. Aerospacelab and Sen will be launching their first demonstrators in 2021. The rest have not started regular launches and most of them will likely not continue.

BlackSky revenues were $22 million in 2020.[94] Planet has not announced funding rounds since early 2019 and perhaps they are currently the only economically sustainable satellite constellation company.

Comparing to late 2017, Planet had launched 180 spacecraft including a single batch of 96 in early 2017. Even 4 years later, no other CubeSat constellation is anywhere near by performance and only Starlink has passed in size. BlackSky had launched their first demonstration mission, while Skybox had already launched 8 by the end of 2017. Astro Digital had two 6U in orbit since 2014 and further prototypes were launched for promising constellation plans, which now seem to have been cancelled.

Latest trend is very-high resolution satellites pursued for example by Albedo Space[91] and Earth Observant,[90] both aiming for approximately 10-cm per pixel resolution, comparable to the capabilities of best military spacecraft.

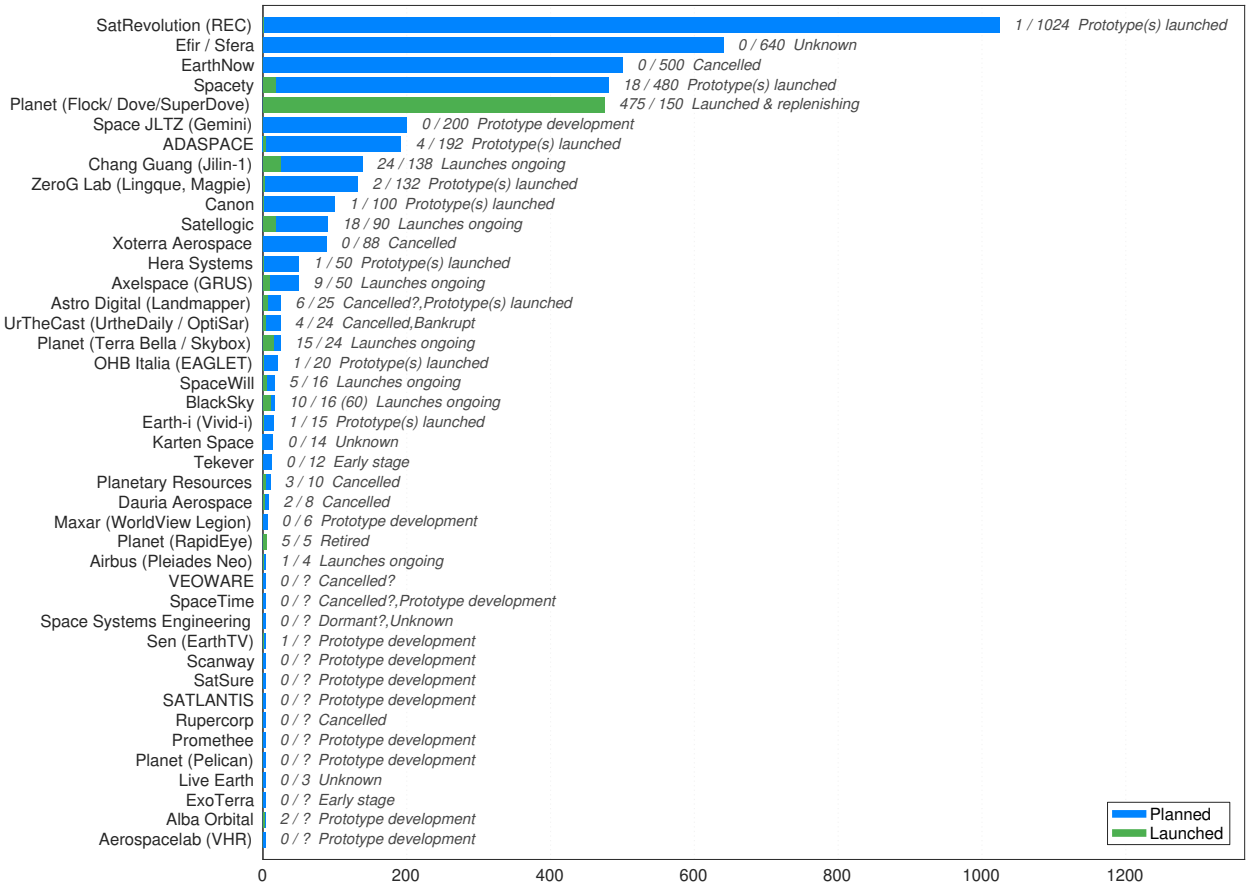

Figure 11: Optical (VNIR) Launched and Planned Spacecraft

Application: Infrared EO

Figure 12 shows Earth Observation constellations in the infrared (IR) and thermal range. Here excluding Near-Infrared (NIR), but including Mid-Wave Infrared (MWIR) and Long-Wave Infrared (LWIR).

Planetary Resources (ConsenSys Space) had 2 spacecraft in orbit by the end of 2017 and was planning a MWIR Earth Observation constellation until bankruptcy and shutdown in 2018.

Aistech Space has launched CubeSat prototypes for ADS-B tracking, but none yet for thermal imagery, after seemingly pivoting the constellation idea to high-resolution IR data, and are now planning a crowdfunding campaign to accelerate development.

OroraTech, ConstelIR and 4pi Lab are aiming to start launching constellations for forest fire detection in 2021-2022. Albedo Space spacecraft will also have a thermal imager in the LWIR range to capture 2-m resolution photos.[91]

Application: Hyperspectral EO

Figure 13 plots Earth Observation constellations with hyperspectral imagers. Satellogic was founded in 2010 and is one of the most accomplished company in the hyperspectral EO after raising $123 million in total and offering imagery with 30 m resolution. They have launched 18 satellites with the first constellation spacecraft reaching orbit in 2016 and plans for 90 satellites in total.[95]

Zhuhai-1 has 8 spacecraft in orbit focused on capturing hyperspectral imagery launched in 2018-2019.[96]

Pixxel, Orbital Sidekick and Wyvern are some of the upcoming constellations entering the same market. Scanway, Scanworld and KP Labs should also launch their first satellites in the next 1-2 years.

Comparing to the end of 2017, Satellogic had launched 3 CubeSats as technology demonstrators and Orbital Sidekick was listed in the database.

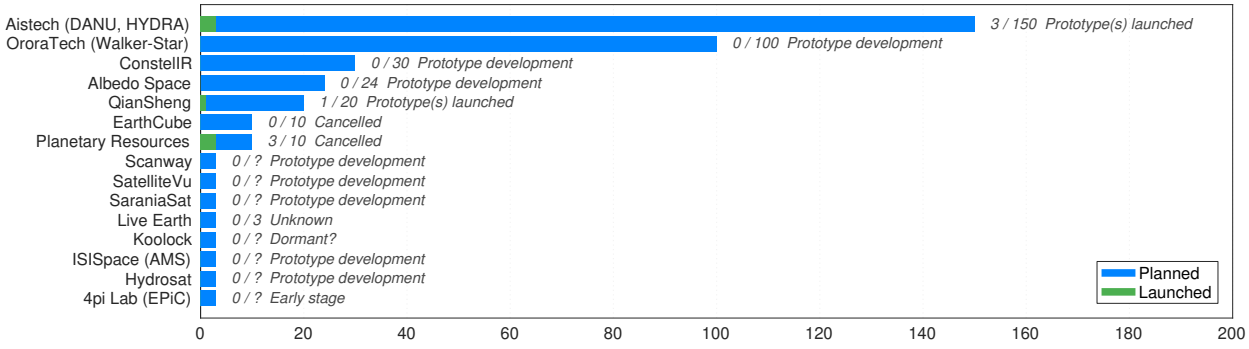

Figure 12: Infrared EO Launched and Planned Spacecraft

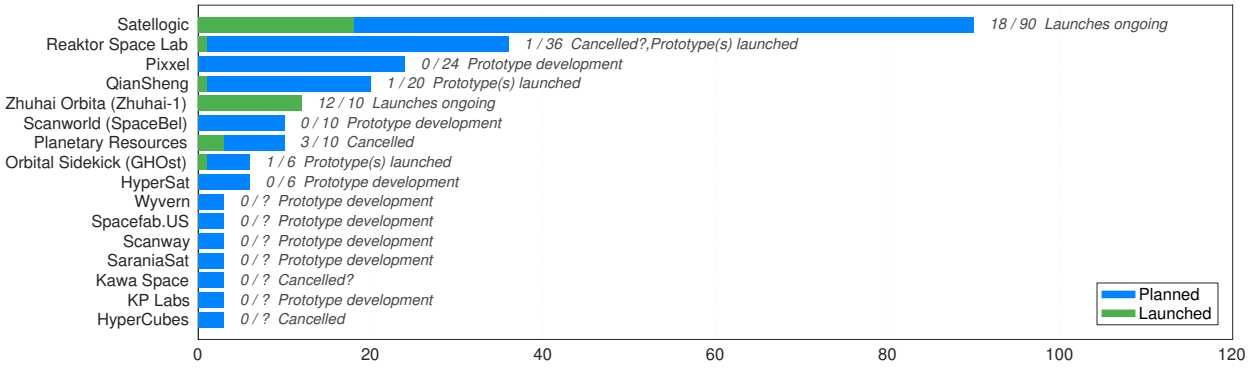

Figure 13: Hyperspectral EO Launched and Planned Spacecraft

Application: SAR

Figure 14 illustrates SAR (Synthetic Aperture Radar) constellations. ICEYE was one of the first to enter this market after being founded in 2014 and has launched 10 SAR payloads since 2018.

Compared to the end of 2017, no commercial SAR satellites had been launched, but in addition to ICEYE intentions had been announced by Capella Space, Umbra and XpressSAR.

Years since have seen many new companies entering this field. Capella has launched 5 spacecraft. During the same time iQPS, Synspective, Spacety, QianSheng have launched first prototypes. Recently PredaSAR, Alpha Insights, Orbital Effects, MDA, EOS and many others have announced plans.

Application: Weather

Figure 15 shows constellations generating data uniquely suited for weather prediction models.

Spire has been the most active with over 140 Lemur-2's launched since 2014 and is offering both GNSS-R and GNSS-RO data. GeoOptics has launched 7 satellites for GNSS-RO measurements.

In the last year, PlanetiQ and Care Weather sent their first prototypes to orbit. In the last months, Tomorrow.io and Climavision[97] have raised large rounds and announced radar satellite constellations.

Application: ADS-B

Figure 16 illustrates ADS-B constellations of which Spire and Aireon (hosted payloads on Iridium-NEXT) are currently offering service. Aerial & Maritime was a partial spin-off of GomSpace, which raised $12.2 million, but never launched satellites and was shut down in 2020 after failing to raise more funding.[98]

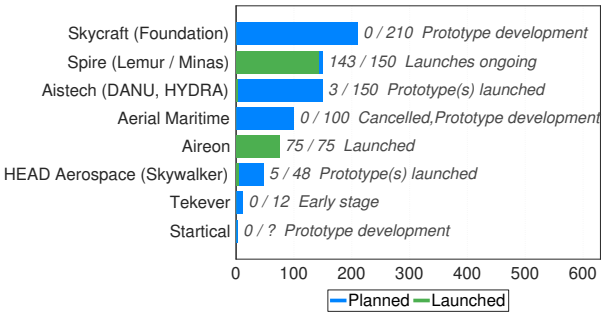

Figure 16: ADS-B Launched and Planned Spacecraft

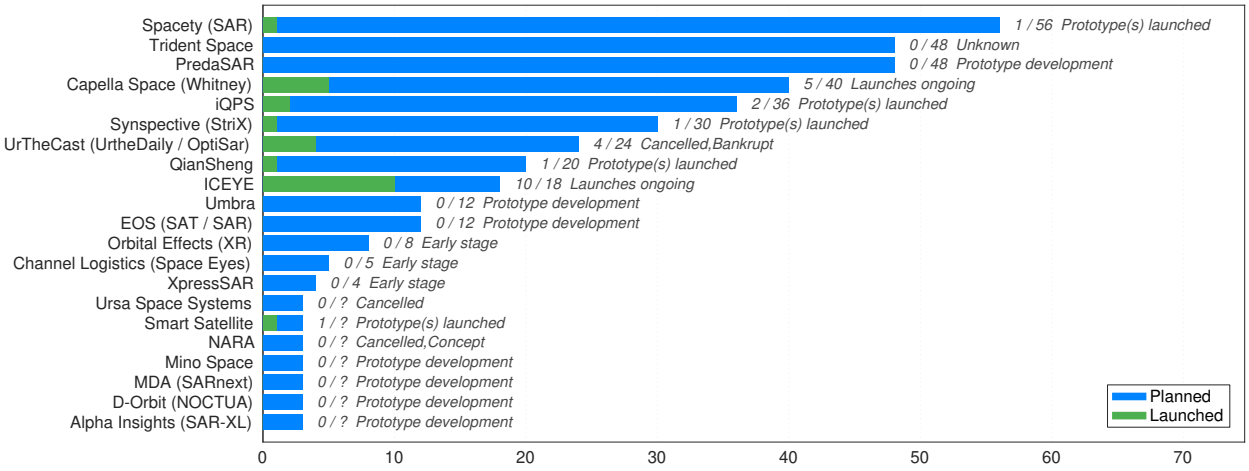

Figure 14: SAR Launched and Planned Spacecraft

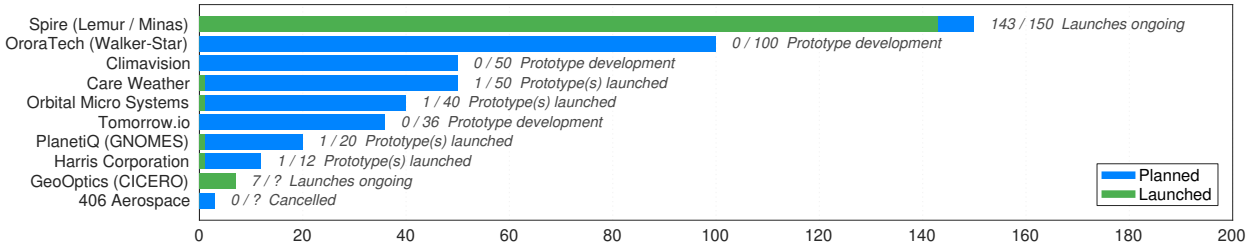

Figure 15: Weather Launched and Planned Spacecraft

Application: AIS

Figure 17 displays AIS constellations, which was one of the first commercial constellation applications. Many student CubeSat teams have performed similar missions. Spire entered the market in 2014 and has the largest constellation. ExactEarth has 58 hosted AIS receiver payloads on Iridium-NEXT.

Spire revenue in 2020 was $28 million[99] and AIS contribution to that was reportedly comparable to Orbcomm and exactEarth revenues.[100]

Many countries have dedicated satellites to receive AIS messages, for example Norway has a series of AISSat and NorSat and Luxembourg recently launched ESAIL with the same mission.

Application: Orbital Data Relay

Figure 18 displays constellations that provide data communications service to other satellites or assets in space. Analytical Space, Kepler and Warpspace are some of the known examples, with the first one possibly having demonstrated service in orbit.

This application will include future lunar space data relay constellations. Airbus SpaceDataHighway GEO-based satellites have been omitted because there are only two spacecraft and alternatively NASA TDRS is not commercial.

Application: VDES

Figure 19 gathers VDES constellations, which is a nascent field and where it will take time for the VDES transmitters to be rolled out, but currently Saab, Sternula and HEAD plan to be ready. It is unclear whether existing HEAD satellites have VDES payload onboard.

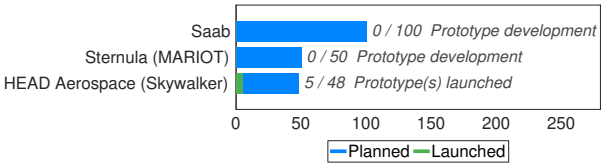

Figure 19: VDES Launched and Planned Spacecraft

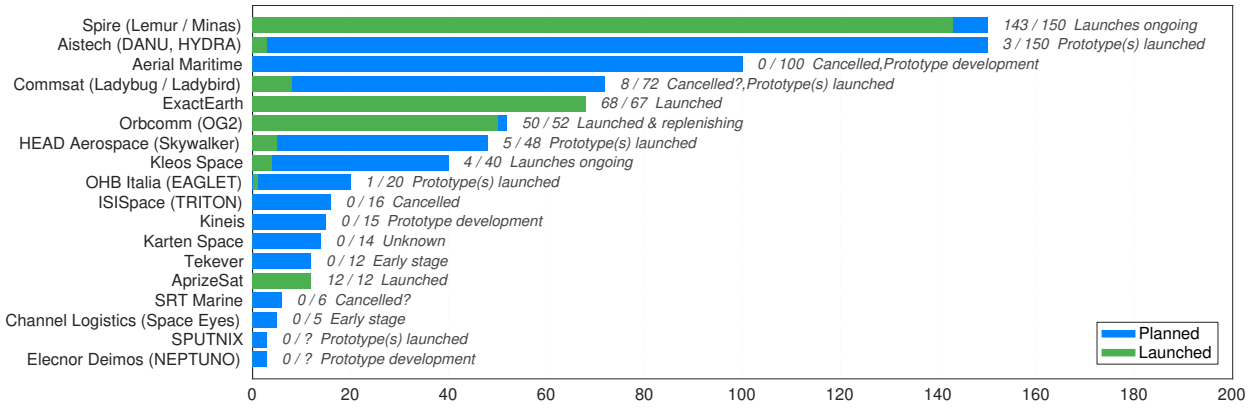

Figure 17: AIS Launched and Planned Spacecraft

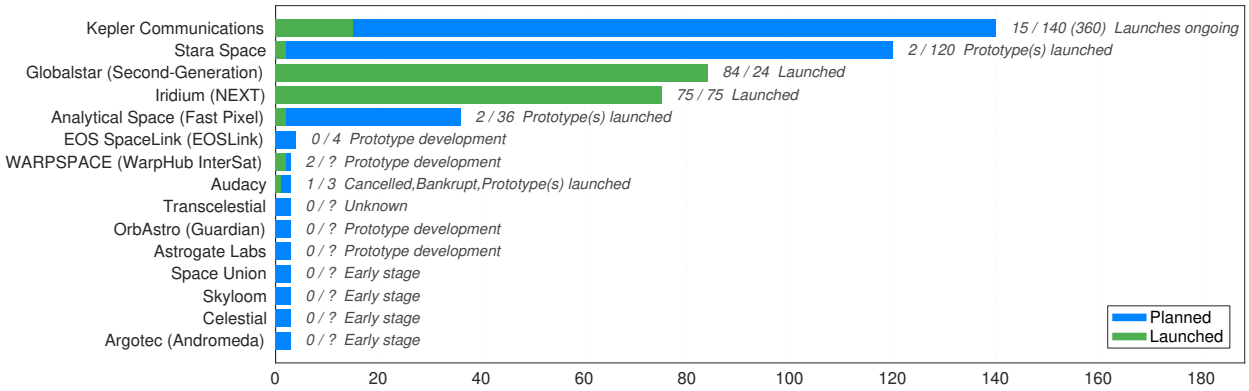

Figure 18: Orbital Data Relay Launched and Planned Spacecraft

Application: Laser Communications

Figure 20 gathers constellations uniquely focused on laser communications between Earth and space. Many others are using optical communications for intersatellite-links. EOS Spacelink bought Audacy assets in 2020, but will not have lasers in the first-generation satellites.[101] QKD could have been included here also due to large overlap in technologies.

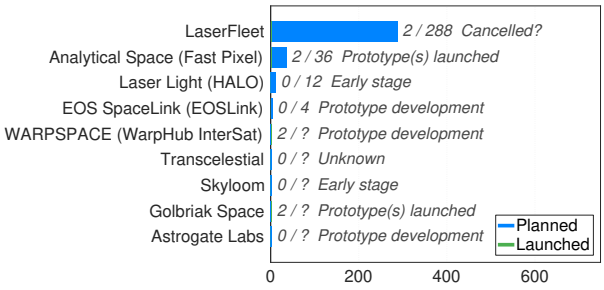

Figure 20: Optical Communications Launched and Planned Spacecraft

Application: RF Spectrum Monitoring

Figure 21 displays constellations detecting radio emissions from objects and likely also performing geolocation. Kleos Space, Unseenlabs, HawkEye 360 and Aurora Insight all have active satellites in orbit and many further launches planned.

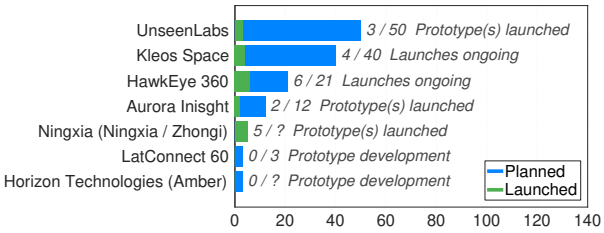

Figure 21: RF Spectrum Monitoring Launched and Planned Spacecraft

Application: Emissions Monitoring

Figure 22 shows companies monitoring greenhouse gas emissions. GHGSat now has 3 satellites in orbit. Bluefield for methane has been delayed for years.

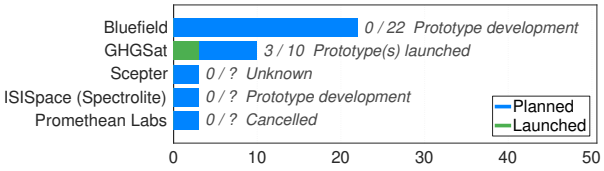

Figure 22: Emissions Monitoring Launched and Planned Spacecraft

Application: GNSS and PNT

Figure 23 represents constellations offering commercial positioning, navigation and timing services. Satelles has hosted payloads on 66 Iridium-NEXT spacecraft.[102] Xona Space Systems raised $1 million pre-seed in 2020 to develop GNSS/PNT services with improved accuracy and encryption using satellites based in LEO.[103]

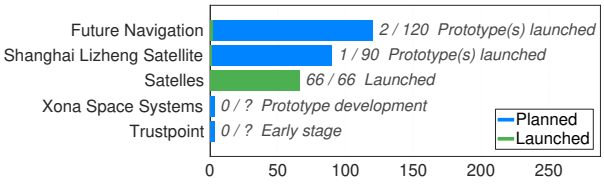

Figure 23: GNSS and PNT Launched and Planned Spacecraft

Application: Constellation-As-A-Service and Hosted Payloads

Figure 24 indicates constellations that host multiple payloads concurrently or are outsourced as a full end-to-end service. In some cases called Satellite-Data-As-A-Service.

Hosted payloads is a concept that emerged early on with CubeSats and microsatellites under the In-Orbit Demonstration (IOD) term with a large number of publicly and internally funded projects and services by now.

Iridium-NEXT is the only operational hosted constellation with Satelles, exactEarth and Aireon as customers. New actors are Loft Orbital, AAC Clyde Space, Spire, Satellogic, Modularity Space and many others. Most of them have first customers contracted for single or even multiple satellites, but long-term viability of this approach has not been proven.

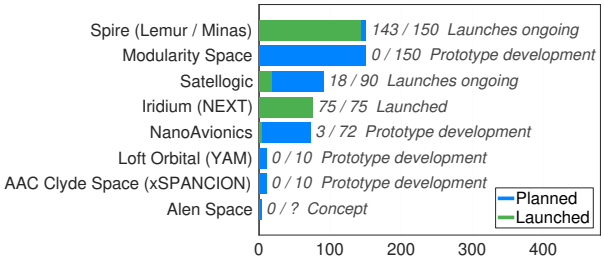

Figure 24: Constellation-As-A-Service and Hosted Payloads Launched and Planned Spacecraft

Application: SSA (Space Situational Awareness)

Figure 25 plots constellations aiming to detect and track other satellites and objects in space for orbit determination. None have been launched, but NorthStar has raised over $43 million and expects to launch its first satellites in 2022.[104]

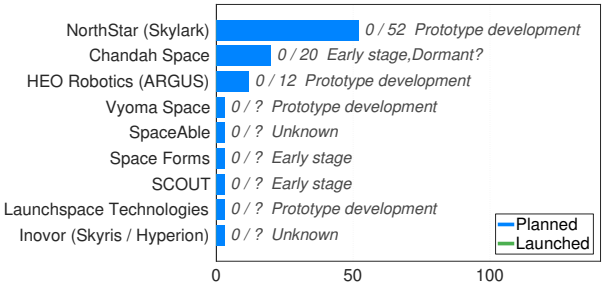

Figure 25: SSA (Space Situational Awareness) Launched and Planned Spacecraft

Application: In-Orbit Inspection

Figure 26 shows constellations aiming to fly close to other satellites and observe their status. None have been launched, but Rogue Space is running a crowdfunding campaign and has established partnership with NanoAvionics.[105] There is overlap with SSA as both can use similar technologies.

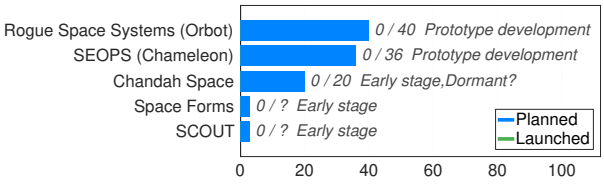

Figure 26: In-Orbit Inspection Launched and Planned Spacecraft

Application: QKD (Quantum Key Distribution)

Figure 27 details QKD constellations for unhackable communications. Chinese test satellite Micius was launched in 2016 and it is still the only one in orbit.[106] Arqit recently announced plans to go public via SPAC while raising $400 million, a deal which is expected to close later in 2021.[107]

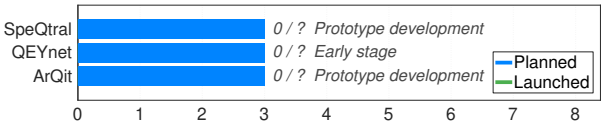

Figure 27: QKD Launched and Planned Spacecraft

Application: Broadband Internet

Figure 28 shows Broadband Internet constellations. These include the largest planned constellations and the most launched satellites up to now. None of them cover the globe yet, but SpaceX expects to achieve uninterrupted service coverage by autumn of 2021 and OneWeb by the end of 2022.

SpaceX Starlink launched two test satellites in 2018, and recently passed 1600 satellites in 2 years from the launch of the first batch of 60 in May 2019.

OneWeb has continued launches after emerging from bankruptcy in 2020 and the total number of spacecraft in orbit is now over 200.

China has had many constellation plans, which as of 2021 May seem to have been consolidated into GuoWang. It is still conceivable that Geely and some others will or aim to deploy their own.

Russia has announced a constellation, but current progress is unknown and likely not commercial. European Union is planning its own constellation too, but possibly not using a commercial approach.

Project Kuiper by Amazon is expected to be a major player in the future, but no satellites have been launched yet. Telesat is another very active stakeholder, which has raised billions and contracted Thales Alenia to build its constellation. Lynk has also performed multiple flight demonstrations. AST & Science has gone public via SPAC and aims to offer Internet directly to mobile phones, but no constellation prototypes have yet been launched.

Application: IoT / M2M

Figure 29 details IoT / M2M constellations and is the largest table with 61 entries. This was one of the first commercial markets pursued by Globalstar, Iridium, Orbcomm and AprizeSat before CubeSats. In recent years and specifically in 2020, many new constellations have launched their first batches, including Swarm, Kepler and Astrocast, all of them using different form factors of CubeSats.

By late 2017, Sky and Space had announced their intention to launch 200 satellites, raised considerable funding and was traded publicly until entering bankruptcy protection in 2020.[108] Sky and Space also had first 3 CubeSats in orbit already in 2017. This partially started an IoT / M2M constellation boom with Hiber, Kepler, Fleet Space, Astrocast, Aistech and dozens more being founded up to now. 3.5 years later Swarm has taken the lead by the number of satellites launched, helped by the small size of 0.25U CubeSats.

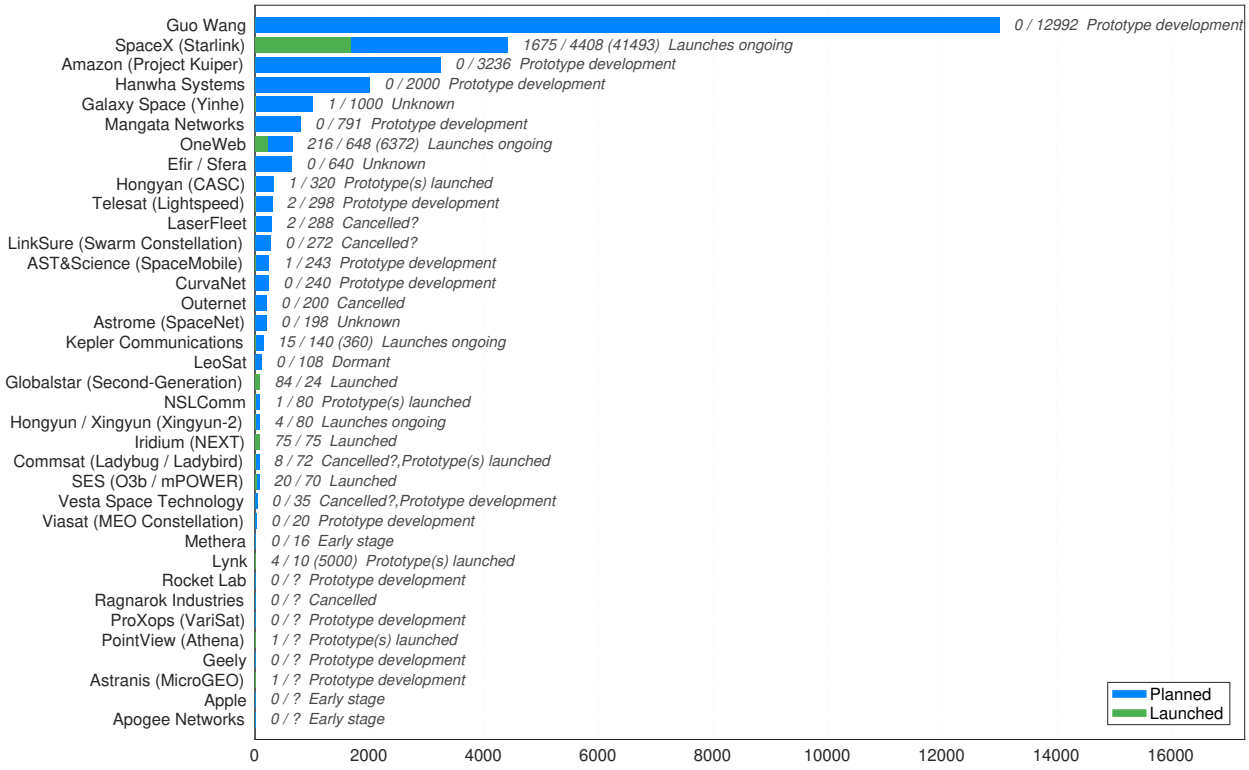

Figure 28: Internet Launched and Planned Spacecraft

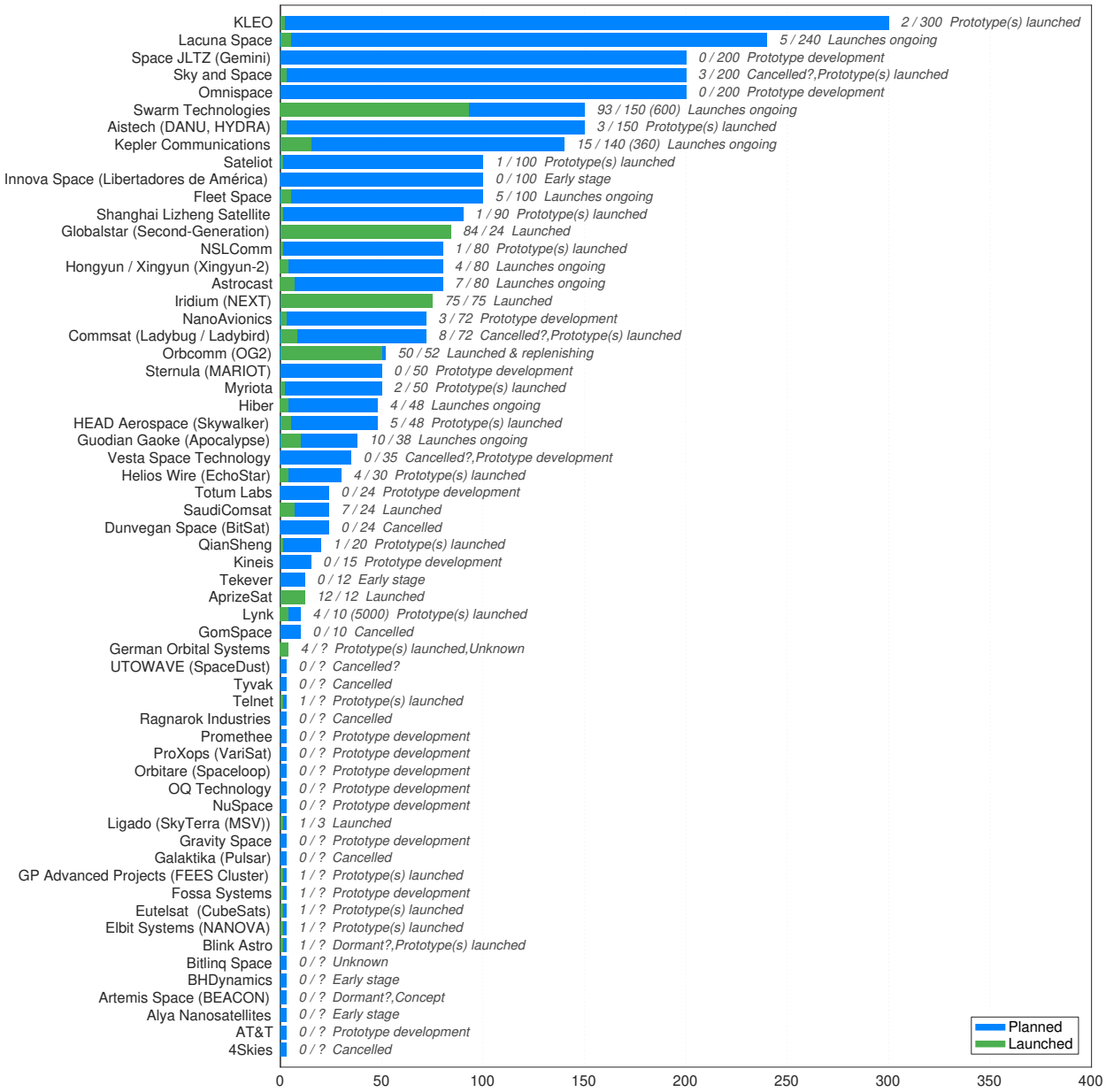

Figure 29: IoT / M2M Launched and Planned Spacecraft

CONSTELLATION TRENDS

Most of the market and technology trend discussions have been integrated into the previous sections under Survey by Applications, Introduction and Statistical Overview, to avoid repeated thoughts. Hereby follows the methodology.

Trends Methodology

Primarily comparing constellations in this survey to a database version from the end of 2017, 3.5 years ago, but also discussing developments before and afterwards. Four approaches to discover trends have been used:

1. Viewing the database entry dates, because majority have been discovered from announcements.
2. Filtering by the founding dates, while acknowledging this will only give a partial picture.
3. Funding news by dates and application types, to better understand growth and execution.
4. Looking at the first launch years, both in the past and upcoming ones, and what progress has been made and at which pace.

All of the four methods combined should give an acceptable view into historic and present trends, because constellation development times are still relatively long and measured in years.

CONCLUSIONS

Statistical overview of 251 commercial satellite constellations has been presented. In addition, the most popular applications were shown in detail and relevant trends were discussed.

Only about 4% of the constellations have been fully launched and approximately 8% are currently being launched. Notable amount of additional entities have raised significant funding and are in active development. Approximately 1/3 of the constellations have already become dormant or cancelled for various technical and non-technical reasons and their quantity is expected to increase.

Broadband Internet constellations are the largest planned satellite networks by size and also have the most spacecraft launched, lead by Starlink. Next in popularity are Optical Earth Observation, SAR, Infrared EO and IoT/M2M. The historically proven applications of Earth Observation, SAR and communications are favoured thanks to existing value chains. AIS has also been a commercial market since early 2000s and now followed by ADS-B.

Latest trends are RF Spectrum Monitoring with Geolocation, Orbital Data Relays, Laser Communications and Emissions Monitoring. Very recent and without prior governmental or commercial satellites are QKD (Quantum Key Distribution), SSA (Space Situational Awareness), commercial GNSS / PNT, VDES, In-orbit Inspection and Constellation-As-A-Service among others.

Future work will foresee studying application specific trends and development timelines in much more detail. Many new applications do not have existing markets, which will take many years to emerge, and/or the revenue potential seems to be small. Major open question is the economic sustainability of most or possibly all of the constellations and this will be researched in a future paper.

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