JOURNAL OF AERONAUTICS AND SPACE TECHNOLOGIES
(ISSN : 1304-0448)
July 2020 Volume 13 Number 2
www.jast.hho.edu.tr

Review Article

Nano and Micro Satellites as the Pillar of the "New Space" Paradigm

Fuat İNCE[1]

[1] *Beykoz University, Faculty of Engineering, 34805 Beykoz, Istanbul Turkey, fince9@gmail.com, https://orcid.org/0000-0003-0829-8609*

Article Info

Received: *March 17, 2020*
Accepted: *June 18, 2020*
Online: *July 27, 2020*

Keywords: New Space Paradigm, nano satellites, micro satellites, small satellites, space industry, space startups

Abstract

Six decades after the launch of the first satellite in 1957, space business and space technologies are taking a new turn: From big to small, from primarily government to extensively private sector and from a few players to profusely many. The new paradigm, or "New Space", as it has been called, can be characterized by new startups with venture capital backing entering the field or in fact leading the field in new innovative applications, universities and countries with no previous space experience joining the bandwagon, lean design and development techniques benefitting from the newly available COTS parts and subsystems, mass production of satellites, constellations of hundreds or thousands of small satellites serving old and new emerging niche needs, small launchers available for reaching orbit at low cost and rather short notice, capability to launch a rocket several times a month, and more exotic applications such as the coming space tourism and asteroid mining. Although there were initiatives in this direction in the previous century, they proved too feeble to set a trend. "New Space" started showing its first signs of emergence after the turn of the millennium. However the market acceptance has really taken root in the last 3 or 4 years. Market data clearly shows an accelerated pace shaping the future of space industry. This paper reviews the developments in the nano and micro satellites considering them as the pillar of the New Space paradigm. The road leading to the present state and the current trends are elaborated. A look to the future points to the proliferation of space applications among the many startups, big and small institutions, however being limited by market forces and survival by a few as the decade proceeds.

To Cite This Article: F. İnce, "Nano and Micro satellites as the Pillar of the "New Space" Paradigm", Journal of Aeronautics and Space Technologies, Vol. 13, No. 2, pp. 235-250, July 2020.

JOURNAL OF AERONAUTICS AND SPACE TECHNOLOGIES
(ISSN : 1304-0448)
July 2020 Volume 13 Number 2
www.jast.hho.edu.tr

"Yeni Uzay" Paradigmasının Temel Direği Olarak, Nano ve Micro Uydular

Makale Bilgisi

Geliş: *17 Mart 2020*
Kabul: *18 Haziran 2020*
Yayın: *27 Temmuz 2020*

Anahtar Kelimeler: Yeni Uzay paradigması, nano uydular, mikro uydular, küçük uydular, uzay endüstrisi, girişimci uzay firmaları

Öz

İlk yapay uydunun 1957'de uzaya çıkışından altmış yıl kadar sonra uzay teknolojileri ve uzay endüstrisi yeni bir dönemece giriyor. Büyükten küçüğe, ağırlıkla hükumetler yerine yaygın özel sektöre, birkaç piyasa hakimi oyuncudan çok sayıda yeni oyuncuya doğru gidişat var. "Yeni Uzay" diye adlandırılan bu paradigmayı karakterize eden özellikler, girişim sermayesi destekli yeni kurulan firmaların bu alana girmesi, hatta bu alana liderlik eder duruma gelmeleri, geçmişte hiç uzay deneyimi olmayan üniversitelerin ve devletlerin bu akıma katılmaları, uydularda kullanılmak üzere ortaya çıkan hazır ticari raf ürünleri ve bunlardan yararlanarak geliştirilen yeni tasarım ve üretim teknikleri, uyduların seri üretimi ve takım uydular halinde eski ve yeni bir takım gereksinimlere cevap verir duruma gelmeleri, küçük uydu fırlatıcılarının ortaya çıkması ve fırlatma maliyetinin ucuzlaması, fırlatma hazırlık süresinin çok kısaltılması, ayda birkaç kez fırlatma yapılabilir duruma gelinmesi ve bunların yanında uzay turizmi ve asteroid madenciliği gibi egzotik uygulamaları ortaya çıkması. Önceki yüzyılda da bu yönde girişimler ortaya çıkmış ise de bunlar bir trend belirlemekte zayıf kaldılar. "Yeni Uzay" belirtileri yeni yüzyılda daha bir güç kazansa da son 3, 4 yılda bir paradigma değişikliği olarak tanınır olmaktadır. Sektördeki veriler artık bu gidişatın gelecekte hızlanarak süreceğini göstermektedir. Bu bildiri Yeni Uzay paradigmasının ana direği olmaları nedeniyle nano ve mikro uydu gelişmelerini ele alınmakta, bugünkü duruma gelirken olan gelişmeler, mevcut projeler ve uygulamalar anlatılmaktadır. Gelecekte uzay uygulamaları, büyük, küçük, yeni, eski, kuruluşlar arasında yaygınlaşarak büyüyecek, ancak bu kuruluşlardan bir kısmı piyasa koşulları içinde yaşamlarını sürdüremezken az sayıda bazıları 2020'lerin sonuna doğru büyüyerek ayakta kalmayı başaracaktır.

1. INTRODUCTION

Although the term "New Space" came into being around the turn of the millennium, it has been the second half of the last decade that the term has really caught on. There is now a journal specifically named New Space [1], covering a wide range of happenings in space technology and the related business environment. The term "New Space" covers the proliferation of nano and micro satellites, small satellite launchers, space tourism, space mining including the asteroids and the Moon, as well as the new entrants into the field, which include public and private institutions, large and small universities, startup companies and countries, with no previous space experience.

This paper will confine its scope to the subject of the micro and nano satellites, because their emergence forms the background and the reason for the emergence of others [2], [3]. In some instances the term "small satellites" will be used which is also common in the space jargon for satellites weighing up to about 500 kg. Access to space and applications of space technologies have brought many benefits to humankind, which can be broadly summarized under the topics of Earth observation, global communications, global navigation, and important scientific discoveries, all with the ensuing industrial and commercial developments that follow. Mankind can now view and monitor any part of the Earth's land, oceans and atmosphere, deriving vital information about natural resources, weather and climate including impending natural disasters. Space technologies have enabled voice, video and data communication between any two points in the world, all in real time. Navigating the oceans and deserts of the world, as well as the streets of crowded cities, which has long been a dream of mankind is now as easy as doing simple arithmetic, thanks to Global Navigation Satellite Systems or GNSS. Gazing into deep space from space telescopes such as Hubble, has not only enhanced our knowledge about the universe but also provided a source of inspiration for more science and scientific education. All that, has been due to the development of space technologies which started at about the middle of the last century.

The first satellites launched in the early days of space, were small by the standards of later years. Sputnik-1 weighed 83 kg and the first US satellite Explorer-1 was just 14 kg. However soon afterwards efforts by the handful of space faring countries concentrated on bigger satellites to accommodate the envisaged communication needs and the defense requirements, mainly led by the two superpowers of the time, USA and Russia (then Soviet Union). In both cases, ie. communication and defense, large size was a necessity using the technologies of the day, lacking the integrated electronics, software control, miniaturized devices and subsystems of the later years. [For an excellent account of the development of small satellites see the article by Sir Martin Sweeting in the Proceedings of the IEEE [4].

Being on the early part of the learning curve and lack or limited availability of space qualified parts and devices, dictated tedious, detailed, time-consuming design and development of all subsystems and components, with rigorous testing, double or triple redundancies, which all resulted in high associated costs and long development times. Only the few space fairing countries of half a century ago, which had the technologies, the required technically skilled manpower, and other necessary resources, could afford the large cost, associated with large satellites and the launchers to put them into orbit.

2. STARTING TO THINK SMALL

Naturally not all satellites were large ones which was the realm of the governments and large corporations. Many "small" satellites were produced and launched along as well. However, these were mostly amateur, educational and research satellites often for testing some new system or proof of concept. Probably the earliest small satellites came from the amateur radio community. The Oscar 1 satellite measuring 30 cm X 25 cm X 12 cm and weighing 10 kg was launched into space in 1961. This was also as the first piggyback or secondary payload riding along a main satellite. Several amateur satellites, or Amsats, followed in the 1960s through the 1980s progressively incorporating new advances in electronics including most importantly programmable microprocessors. [5], [6].

The so-called small satellite concept owes its beginning much to the efforts of Sir Martin Sweeting and the group of young engineers around him in the University of Surrey in the UK. The Surrey group started to become a focal point in small satellite technology in the 1980s, by a new approach to satellite design and production, using inexpensive off the shelf components, reducing not only the size but also the cost and the development time of satellites. The success of their Earth observation satellites in the 100 - 200 kg range became the basis of technology transfer to third World countries who then started building their own small satellites with Surrey assistance and cooperation. Under Surrey leadership these countries formed a so-called Disaster Monitoring Constellation or DMC. The initial Surrey University group has now developed into one of the leading satellite manufacturers in Europe known as SSTL (Surrey Satellite Technologies Limited). Although they were acquired by EADS Astrium in 2008, they continue to act independently.

There were also some distinct initiatives in the US, to conceptually produce smaller less costly satellites from both amateur and professional sources. One example is the now defunct AeroAstro Corporation of Rick Fleeter, [7], [8] who started the company in 1988 in line with the motto of the day, "smaller cheaper better". His dedication of the concept of "microspace" was unique for the day, foreshadowing the development of a decade or two later. Under "microspace" he promoted the idea that small spacecraft can be built with a minimum of facilities, based on simple reliable architectures, reducing the infrastructure requirements.

Despite Dr Fleeter's new ideas on small satellite development, the concept of individual design and development of "one of a kind ", was still the same, whether it was large or small. Smaller ones did take proportionately less time and resources, but followed the same design and development approach as with those of the bigger satellites although parts of earlier designs did start to appear in the new ones. This can be attributed to the lack of miniaturized electronics and MEMS (Micro Electro-Mechanical Systems) parts which were yet to come to the space qualified market.

Although small satellites have been produced all through the space age, the thinking behind the "New Space" approach has been markedly different from the traditional one where heavy technical, organizational rules of large corporations and special space proven hardware resulted in high costs and long design and production times.

However, that design approach started changing drastically around the turn of the century. The new approach employed small highly competent and motivated engineering teams working together, under knowledgeable and foresighted management, focused on a well-defined, clear cost and time objectives, making use of new design techniques, new miniaturized integrated hardware, with new software and networking concepts.

It is worth mentioning at this point the contribution, to the small satellite concept, of the Small Satellite Conference (SSC) which started in 1987 at Utah State University [9] and continues to this day at the same location with increasing attendance and popularity. Many new ideas and innovative projects came out of the SSC, including that of the Cubesat.

3. ARRIVAL OF THE CUBESAT

The most critical development in going smaller, was the idea of Cubesat, [10], [11] proposed jointly by Jordi Puig-Suari of California Polytech State University and Bob Twiggs, then at Stanford University. A standard cubesat was defined as a cube with 10 cm on each side and a maximum mass of 1 kg. This so called one unit or 1U could be doubled to 2U (20 X 10 X 10) or tripled to 3U

(30 X 10 X 10), which has now grown to 12U at the last count, with 27U in the planning. Cubesats were initially proposed to facilitate and enable student projects and thus promote education and learning not possible with large satellites. However, they soon became the tool for many other scientific, and commercial projects as the examples below will show.

The concept of a standard cubesat soon led to the production of many standard cubesat components and subsystems. As economies of scale kicked in, these became available in the market as COTS (Commercial Off The Shelf) parts and at very reasonable prices. Soon universities were producing cubesats within modest budgets in the order of only a few tens of thousands of dollars. Companies both large and small also started taking advantage of the cubesat concept, followed by space agencies and governments of different countries. Cubesats are more formally described as a class of nanosatellites, i.e. those between 1 kg and 10 kg mass. For the last two decades or so, as satellite sizes varied by four or more orders of magnitude, different schemes for classifying satellites have emerged. The differences occur at the heavier part of the classification scale above 100 kg. However there is general acceptance on the terms used for the lower end, which are: micro (10-100 kg.), nano (1-10 kg), pico (0.1-1 kg) and femto (less than 0.1 kg) satellites. The term "mini satellite" has been used for the range from 100 kg. to 250 kg. or to 500 kg. or even more. There is even a bigger ambiguity when it comes to the use of "small satellite" which can mean anything in the range from 1 kg to 1000 kg, in various publications. In the rest of this paper, when we write "nano and micro satellites", we will stick with the widely accepted meanings as above. Sometimes the term "small satellite" may be used to mean masses up to about 250 kg [12].

4. MICRO AND NANO SATELLITES DOMINATING THE SPACE SCENE

The saying "cheaper by the dozen" seems to be an appropriate term describing the number of micro and nanosatellites being launched currently and as planned in the near future. This proliferation seems to span almost the whole range of satellite applications although certain limitations do exit necessitating larger satellites.

Invigorated by technological developments and thinking small, the satellite scene is dominated today, by the sheer numbers of micro and nano satellites. The estimates of the micro and nano satellites going into orbit in the coming years is expressed in thousands as already exemplified by those launched to date (end 2019). Below are given a sample from the hundreds of such satellites, launched with a variety of different missions, picked to exemplify the range of applications and developer or owner institutions. An exhaustive list would be much beyond the coverage of this article.

4.1. Communications

When space communication is mentioned, one normally thinks about large telecom satellites at GEO, although LEO constellations of some tens of smaller satellites such as the Iridium constellation also exist [13]. Now very large constellations of nano and micro satellites are entering service in different communication areas such as internet and IoT connectivity, from brand new space startups, to well-known companies with large capital to invest in new areas. The latter group includes those with extensive space background such as Space-X [14], as well as those with practically no space experience but large capital, such as Amazon. These companies and others, mostly startups of the last few years, hope to eventually establish constellations containing hundreds or thousands of satellites fulfilling various communication needs. Amazon [15], [16], has announced it has filed for a license to operate a constellation of 3,234 satellites in low orbits, whereas Space-X has already started on launching the first batches of its planned constellation, initially planned for 12 000+ satellites, but could go much higher. There are still other companies which have announced plans for constellations in the hundreds.

However now side by side with these well-established giants, are new startups formed by a few forward looking, technical and business people largely using venture capital, emerging as successful entrepreneurs of a niche communications satellite business.

OneWeb, is (was?) a UK based communications company, on the way to creating a constellation of satellites that will provide broadband Internet access to users around the world fully covering the Earth's surface. A venture-backed startup with funding from Japan's SoftBank, Airbus and chipmaker Qualcomm, OneWeb sent up its first batch of satellites in February 2019, planning its next three launches in the first half of 2020, eventually reaching 2,000 satellites by 2026. Initial constellation of 650 satellites would begin to provide commercial services in 2021 [17], [18], [19]. However during the review process of this paper OneWeb announced its bankruptcy, partially blamed on the general economic downturn due to the corona epidemic.

A Dutch space startup, Hiber, plans to expand IoT (Internet of Things) connectivity to 90% of the world that currently lacks a network. Hiber was founded in 2016 with the sole aim to provide IoT connectivity globally at a low cost and low power, making sure that there was a network that allowed anyone in the world to share data, wherever they were, in remote places from the middle of the ocean to Antarctica or the vast desert. Having launched their first two nanosatellites in 2018, Hiber plans of launching and operating an unspecified number of dozens of satellites to meet the demand for IoT connection services from Africa to Antarctica. The solarpowered satellites will collect data beamed up from a modem connected to IoT devices on the ground where connectivity is poor or non-existent and relay them back to Earth. Hiber focuses on a variety of applications, notably agriculture, soil and rain sensors, tank and silo monitoring, snow and ice cap monitoring, transportation and logistics [20].

The advantages of micro satellite over larger ones which include small antenna and low latency, make them more suitable for short messages, short data packages, vehicle tracking, remote location data transfer and the burgeoning need for IOT (Internet of things). Constellations of micro satellites should also provide affordable global internet access for remote corners of the World, which are now lacking such service or very inadequately served.

On the other hand these constellations will compete with other space based, ground based and aerial platforms and networks. By the mid 2020s these companies as well as possible new comers will either prove themselves or may go defunct. Time will show which companies will eventually succeed and which will fail in the market for space based communication services, how the startups will fare with the well established giants and other competitors.

4.2. Earth Observations (Remote Sensing)

Remote sensing satellites used in Earth observation can be classified in three main groups depending on the technology and region of the EM spectrum: Optical/multispectral, Synthetic Aperture Radar (SAR), and RF sensing. The last one is mainly of interest to the military community for mapping of RF emitters of the adversary.

Constellations of commercial nano and micro satellites for optical/multispectral remote sensing have already been operating since 2013. Planet Labs [www.planet.com] of US has led this field. However soon it is to be joined by other companies and government institutions. We are also witnessing SAR remote sensing constellations coming into use by startups, such as by Iceye of Finland [21].

High resolution remote sensing has been the realm of sophisticated government satellites or those of well known space companies such as Lockheed, Aerospace Corporation and Ball Aerospace. In recent years however new companies have successfully entered the field with micro and nano satellites providing 1-5 meter range resolution anywhere on Earth to Worldwide customers. In addition, many universities are launching student built satellites for research and technology demonstration purposes.

Planet Labs is a company based in San Francisco, USA, which designs, builds, and launches nano and micro satellites. Having launched their first two satellites in 2013, the company builds and launches a new set of satellites every three or four months. Planet's nano and micro satellites, which are in-house designed and built, image the entire Earth several times daily at resolutions of 1-5 meters. The in-house capability allows them to incorporate the latest technology into their nano and micro satellites, "using lean, low-cost electronics and iterative design techniques". They call their 140+ satellites "our doves", which make up the world's largest constellation of Earth-imaging satellites circling the Earth at different inclination angles. With 45 ground stations throughout the World, they try to address the needs of a whole range of customers from local and national governments to private companies, institutions down to individual farmers and citizens groups [22].

Spire Global of Glasgow, is another Earth observation company recently started by launching nanosatellites with the aim of global monitoring, to track aircraft, ships and weather patterns. The supercomputing scalable devices aboard their nanosatellites can be programmed to process data while in orbit. This enables them to analyze and select high-quality data and immediately transfer it to Earth from a large constellation of over 80 nanosatellites that report to a global network of ground stations. An innovative approach of Spire Global is using the parallel supercomputing devices for considerable on-board processing to limit the amount of data to download. To quote the company's CEO. "Just one of our small satellites can collect over a terrabyte of data per day, which would be prohibitive to download. It has to be analyzed and processed in orbit so that true insights can be delivered to customers directly and in a timely fashion. We see these parallel supercomputing scalable satellites as being extremely important for the next phase of Earth observation applications for the benefit of all mankind." [23], [24].

A noteworthy use of cubesats comes from The Aerospace Corporation's CubeSat Multispectral Observing System (CUMULOS), proving their utility in an application which was deemed to be the realm of larger satellites. CUMULOS "has reached another major milestone-taking calibrated nighttime images from 280 miles above several major cities worldwide)." CUMULOS uses point-and-stare imaging to keep pixels on target for up to one-half of a second to achieve excellent light sensitivity and focuses on selected scenes with a telephoto lens to deliver over five times the spatial resolution of current scanning polar-orbiting satellites. "CUMULOS has proven that CubeSats can provide good-quality, higher-resolution nighttime images of city lights and other bright targets at a fraction of the cost of larger satellites … " [25]

It was noted above that universities have been active promoters of cubesat technology. A couple of notable examples from dozens are given here. A Colorado State

University experimental satellite is operating after more than one year in low-Earth orbit, demonstrating its small satellite weather forecasting capabilities. TEMPEST-D (Temporal Experiment for Storms and Tropical Systems - Demonstration), a type of small satellite called a 6U CubeSat, is providing precise images of global weather. Carrying a miniaturized microwave radiometer, the cubesat is measuring at five frequencies, TEMPEST-D can see through clouds to reveal the interior of storms where raindrops and ice crystals form. "TEMPEST-D is the first weather satellite on a CubeSat to image the interior of storms on a global basis," [26]

The Ben Gurion University in Israel has shown the proof of concept for a nano-satellite System which produces submeter high resolution imagery, hitherto thought possible only with larger satellites. As revealed by a study, published in the journal Optica, groups of small nano-satellites when arranged in a ring shape, can focus light onto another imaging satellite, producing images rivaling those of full-frame, lens-based or concave mirror systems. The university researchers have not yet built such a satellite. However have built a laboratory model of their invention showing proof of concept. Researchers were able to capture high-resolution images using only a tiny fraction of a full lens on each nano-satellite model. This development could slash the cost time and material needed for large optical space cameras, revolutionizing space imagery as nanosatellites are much cheaper to build and launch [27].

It seems micro satellites are close to achieving near parity with large ones in at least two respects, regarding remote sensing. First, in terms of ground resolution at or near one meter, perhaps a factor of 1:2 or 1:3 has been achieved at much less cost and with other advantages as will be explained below. This is regarding the civilian satellites, not accounting for the secret military reconnaissance imaging satellites. The second aspect is how the imagery can be obtained commercially by any nation whether space faring or not, at reasonable cost and in timely manner. Soon, many non space faring nations are expected to build and launch their own remote sensing satellites, mainly optical/multispectral, to independently meet their environmental, economic and security needs, although they may not be at the same technology level as space faring nations.

Again the emerging imaging satellite constellations will be in competition with each other and with other ground and aerial platforms including UAVs and balloons. It is expected that eventually market conditions will dictate their success or failure.

4.3. Science and Technology Development

One of the main areas of cubesat applications is actually science and technology [28]. In this regard, the first institution that comes to mind is NASA, followed by ESA and other space agencies, some universities, research institutions and also the military pursuing the technology developments for its own use.
NASA is making use of cubesats in a number of space missions, as given briefly below and quoted directly from NASA’s web sites [29], [30], [31], [32], [33], [34], [35].
“CIRIS, a Compact Infrared Radiometer in Space instrument on a CubeSat, was launched from Cape Canaveral Air Force Station in Florida to the International Space Station on Dec. 5 (2019). The backpack-sized satellite is aiming to collect, process and calibrate infrared images to reveal Earth’s temperature for the first time from a small satellite.

The Lunar IceCube mission, led by Morehead State University in Morehead, Kentucky, will study water distribution and interaction on the Moon. The mission will carry a NASA instrument called Broadband InfraRed Compact High-Resolution Exploration Spectrometer (BIRCHES) to investigate the distribution of water and other organic volatiles. Lunar IceCube, is a CubeSat which weighs 31 pounds, and provides the agency with an efficient and cost-effective way to study the Moon.
Designed and built at NASA's Jet Propulsion Laboratory in Pasadena, California, as a technology demonstration, MarCO launched to the Red Planet in 2018 with NASA's Insight lander. Using experimental radios and antennas, the pair relayed signals back to Earth that enabled InSight's team to observe the spacecraft's Nov. 26, 2018, entry, descent and landing on Mars in near real-time.
NASA has awarded a $13.7 million contract to Advanced Space of Boulder, Colorado, to develop and operate a CubeSat mission to lunar orbit as an orbiting outpost astronauts will visit before descending to the surface of the Moon in a landing system as part of NASA’s program. The CubeSat is expected to be the first spacecraft to operate in a near rectilinear halo orbit around the Moon.

A new view of Hurricane Dorian shows the layers of the storm, as seen by an experimental NASA weather satellite that's the size of a cereal box. TEMPEST-D [120], reveals rain bands in four layers of the storm as Hurricane Dorian approaches Florida on Sept. 3, 2019. Known as a CubeSat, TEMPEST-D uses a miniaturized version of a microwave radiometer to successfully track storms like Dorian. The technology demonstration could lead to a train of small satellites that work together to track storms around the world.

NASA is seeking proposals from U.S. small satellite developers to fly their CubeSat missions as secondary payloads aboard the SLS [Space Launch System] on the Artemis 2 mission to the Moon, under the agency's CubeSat Launch Initiative (CSLI). CSLI provides CubeSat developers a low-cost pathway to conduct research in space that advances NASA's strategic goals in the areas of science, exploration, technology development, education and operations. The initiative allows students, teachers and faculty to gain hands-on experience designing, building, and operating these small research satellites, which are much less expensive to produce than traditional satellites.

NASA's twin E-TBEx CubeSats are scheduled to launch in June 2019 aboard the Department of Defense's Space Test Program-2 launch. The launch includes a total of 24 satellites from government and research institutions. The E-TBEx CubeSats focus on how radio signals that pass through Earth's upper atmosphere can be distorted by structured bubbles in this region, called the ionosphere. These distortions can interfere with military and airline communications as well as GPS signals.
And ChipSats: Stanford and NASA Ames researchers put inexpensive chip-size satellites into orbit. On June 3, as NASA Ames Research Center announces the successful deployment of the largest swarm of ChipSats in history, deploying 105 ChipSats into low-Earth orbit on March 18. The next day, detected the signals they sent one another, demonstrating their ability to communicate as a group, a prerequisite to operating as a swarm. Each ChipSat is a circuit board slightly larger than a postage stamp. Built for under $100 apiece, each ChipSat uses solar cells to power its essential systems: the radio, microcontroller and sensors that enable each device to locate and communicate with its peers.
NASA's SIMPLEx program has two lunar science missions in the works: LunaH-Map, a CubeSat mission to measure hydrogen concentrations on the lunar surface, and Lunar Trailblazer, a small orbiter that will map water ice deposits by using infrared instruments. "LunaH-Map is pronounced 'Luna-Map' because it is looking for hydrogen, … "
NASA is also assisting many startups and universities in the US, building cubesats and providing them free launch assistance. An example is the group of Virginia Tech undergraduate students who delivered their cubesat to NASA, to be launched. Virginia Tech's satellite, along with two satellites from other Virginia universities, was built by undergraduate students. Over the last several years, an interdisciplinary team of 50 undergraduate students from the College of Engineering and the College of Science developed Virginia Tech's CubeSat at the Center for Space Science and Engineering Research. The project's mission is to obtain measurements of the properties of the Earth's atmosphere in low earth orbit. As the orbits of the satellites decay due to atmospheric drag, the satellite instruments will quantify atmospheric density." [36].

Naturally NASA is not alone in science and technology development projects using nano and micro satellites. There are also many startups developing communications technologies for the future, one such company being Aralis testing its receivers in the K Ka bands on micro satellites [37].
In Europe, ESA has set up a new CubeSat Systems Unit at its ESTEC Technical Centre in the Netherlands, specifically to promote cubesats and regarded as a center for smaller missions to space. It has been planned as a centre of excellence, building up deep expertise in miniaturized technology and equipment, to serve cubesat projects in both industry and countries across the continent [38].

In addition to regular small payloads, ESA is especially utilizing cubesats for in-orbit testing and demonstration of new technologies and new concepts. Current and future cubesat missions include exploring near-Earth asteroids, testing micro propulsion devices, developing intersatellite communications for expedited data relay to Earth, ozone monitoring, studying atmospheric reentry, solar radiation and a double cubesat mission to test rendezvous and docking techniques. [39], [40], [41].
ESA is maintaining close relations with industry, working with many small to medium sized European companies to ensure European companies follow and lead the state of the art in this new part of the space sector. Europe's CubeSat industry is made up of dozens of companies, which through close ESA support and collaboration, embark on commercial exploitation of the developed technologies. ESA conducts CubeSat Industry Days, taking place every two years, with increasing attendance which reached nearly 300 participants last year from over 150 different organizations [42].
One of ESA's cubesat missions is on the way to an planetary journey, just like two NASA cubesats which went to Mars, on a distinct relay service. When ESA's planned Hera mission journeys to its target binary asteroid system, it will carry two tiny CubeSats for deployment around - and eventual landing on - the Didymos asteroids [43].

Three of the European companies mentioned above, OneWeb [17], Spire [23], and Hiber [20], are actually startups in this field of New Space. These companies are applying the new technology to new or old market needs. Others like Gomspace of Denmark are actually developing basic cubesat technology with new systems, subsystems and devices for use by others who wish to enter the field using COTS parts. Gomspace has emerged from a startup in 2003 to now being a leader in cubesat technology with a solid tract record of successful cubesat projects.

"ESA has signed a contract with Gomspace [44], [45] to develop *a miniaturized electric propulsion system suitable for small spacecrafts going on interplanetary missions."* The contract will be carried out under ESA's General Support Technology Program through 2020 and 2021, at a value of EUR 700,000. The project will expand propulsion capabilities to span both cold-gas technology for station-keeping, collision avoidance and maneuvering as well as electric propulsion technology for orbit changes, e.g. for safely disposing of spacecraft after the end of a mission.

ESA is also supporting and cooperating with universities in nanosat projects. Graz University in Austria, launched in December 2019, a nanosatellite named OPS-SAT, which was supported by ESA and is being controlled from ESA's European Space Operations Centre in Darmstadt, Germany. It is to carry out certain hardware and software tests directly in the course of flight, which until now, have been made on much larger satellites, thus validating new operating concepts of cubesats as a "flying laboratory" in orbit. [46], [47].

UK, apart from being an ESA member, is onto an ambitious space program of its own. The UK government is trying to ensure a leading role for the country, in the age of New Space as part of its modern industrial strategy, in particular with support for domestic satellite launch capability and in space weather forecasting. This is in addition to at least one company, SSTL (Surrey Satellite Technology Ltd, which has been a World leader in small satellites since the 1990s. It should also be noted that OneWeb, and Spire mentioned above, as ambitious new startups with nano and micro satellite constellations, are already UK based companies [48], [49].

UK Space Agency is planning a spaceport at Cornwall, that would enable small satellite launches from there in the 2020s. The investment at the Cornwall horizontal launch capability has the financial support of both the local council and that of Virgin Orbit of the US, which is expected to be the first customer to use the facility. Virgin orbit is entering the small satellite launcher market with their aerial launch system [50].

SULIS is a UK-led solar science mission, designed to answer fundamental questions about the physics of solar storms. The mission consists of a cluster of cubesats and will carefully monitor solar storms using state-of-the-art UK technology, as well as demonstrating new technologies in space. SULIS will include instruments to directly measure the magnetic field of the solar corona for the first time, with three pairs of formation-flying coronagraphs in orbit around the Sun. SULIS is not only designed to be a space science mission, but also to demonstrate technology for precision alignment of small satellites flying in formation, and future communications [51].

Two of the UK's leading space sector companies, Surrey Satellite Technology Ltd (SSTL) and Oxford Space Systems (OSS) have been awarded funding by the National Space Technology Program, to develop an innovative Synthetic Aperture Radar (SAR) payload planned for launch in 2021. This new technology delivers a truly disruptive solution and is a key enabler for the next generation of SAR services from orbit. The innovative SAR payload will be exclusively developed in the UK employing a high bandwidth radar instrument and RF system from SSTL [52], [53].

Another startup, this time from Finland, is Iceye, which is also developing a micro satellite based SAR constellation, specifically aimed at monitoring the polar regions. The company claims to be the first organization in the World to successfully launch SAR satellites under 100 kg. They aim to provide coverage of selected areas every few hours, day and night for applications in maritime, disaster management, insurance, finance, security and intelligence [21].

From Canada, microspace work at the Space Flight Laboratory (SFL) of the University of Toronto, is worthy of attention. SFL which was established in 1998 as a self-sustaining specialty lab at the university's Institute for Aerospace Studies (UTIAS), provides end-to-end microspace services for clients around the world. Over two decades, SFL has developed 25 nano and micro satellites that have been launched for missions in space science, Earth observation, communication, radio frequency geolocation, environmental monitoring, technology demonstration, and ship detection. Satellites, developed on tight schedules and at low cost, have reached 100 cumulative years of on-orbit operations to delivering significant returns to the different customers. [54], [55].

Several universities around the World have been developing cubesats since the turn of the century, with a wide range of missions. Tokyo University has been a pioneer in this field along with several universities in the US including CalPoly and others. One notable example outside of that group has been Istanbul Technical University in Turkey and its Astronautical Engineering Department, which started developing their first 1U cubesat, the ITUpSat1, in 2005. Signals from that satellite, which was launched to an SSO orbit in 2009, are still being monitored. Four more cubesats of 2U and 3U sizes have been developed and launched since then with support and launch collaboration from national and international organizations [56], [57].

4.4. Defense

Space power plays a vital role in almost any military operation as recognized by all the major powers since the first days of space access. Uninterrupted availability of space assets in providing valuable reconnaissance, surveillance, communication and navigation services, has become of utmost importance for success, in fact for survivability, in any military conflict. Protecting one's own assets and replenishing those lost due to enemy action, are two challenges which the militaries face in ensuring the sustained benefits from space.

Micro and nano satellites have naturally occupied an important place in the agendas of the global defense sector as well. They offer definite advantages in providing, and more importantly, in maintaining space capabilities in the face of losses, thus boosting space power beyond those provided by larger satellites alone. The short time to build and launch a nano or micro satellite, the ability to incorporate new technology in a short development time, the resiliency of a constellation to losses of one or a few satellites, the short revisit times and the cost of such satellites are obvious advantages over large ones [58].

Military use of nano and micro satellites would normally differ from civilian use, in that they are part of a larger information fusion process. They would serve targeting and situational awareness purposes in an integrated fashion with optical, SAR and RF mapping satellites of various sizes, making use of the ubiquitous GNSS, automatic identification systems, and actual instantaneous weather monitoring in connection with command and control centers. Integration of information becomes more robust and reliable when coming from a variety of sources such as from constellations of satellites. It is well known that space powers including, US, China, Russia, and others, have been developing their small satellite capabilities, in full recognition of the importance of the advantages offered by them. NATO, in its meeting of the foreign ministers in November 2019, formally declared space as the fifth military frontier along with land, sea, air and cyber. Although not explicitly stated, NATO too must have micro and nano satellites in its agenda as in the space agendas of the defense communities in all the space faring countries, [59], [60].

US Defense Department has promoted "small satellites" to a certain degree since early 1990s. However closer involvement in the new technology has emerged in the last several years, to keep abreast of the developments in the commercial sector and see how the developments there can serve its own needs in a much more cost effective way. Contemplations are fueled by ambitious predictions that the new generation of light, cheap, disposable satellites could cut down the cost per satellite from around $1 billion to only a few of million dollars. The US program is managed by the DoD's Defense Advanced Research Projects Agency (DARPA). In May 2019, DARPA announced a three-phase contract program totaling $117.5 million to develop a set of cheap, lightweight satellites based on advances already made in the field by the commercial sector. In the new program, DARPA hopes to have 20 prototype surveillance / reconnaissance satellites in LEO by 2021, if it can reach the target price of $6 million per unit [61].

It is reported by Space.com that "The US's present reconnaissance satellites are huge, lumbering, expensive, ancient things. They cost upwards of a billion dollars and take a decade to develop, ensuring they're out of date by the time they even get launched. However the program, spearheaded by DARPA could revolutionize the industry and make all that a thing of the past."

DARPA has also contracted Lockheed Martin to produce another kind of micro satellite as well: The Segmented Planar Imaging Detector for Electro-Optical Reconnaissance (SPIDER), which is to have a tiny, one-inch-wide sensor. It is expected that the new unit will reduce the weight and size of a traditional space camera by 90 percent by replacing large, bulky mirrors and lenses with a tiny array of lenses [62].

Outside of DARPA, the US Air Force is also developing plans to invest in the new paradigm. Already, Pearl White, an Air Force Space Command demonstration program, has launched two 6U cubesats as experimental spacecraft for on-orbit testing of emerging technologies in 2019. The demonstration will test new technologies including propulsion, power, communications, and drag characteristics for potential applications on future spacecraft. The two cubesats are designed for a one-year lifetime [63], [64].

5. DISCUSSION AND CONCLUSION

The small satellite ecosystem is entering a new phase, labelled as "New Space", where satellites, much smaller than the traditional ones, are being produced and launched by the dozens or hundreds or even thousands, by institutions, government or private, big or small, old or newly established. The new technology of the micro and nano satellites makes them more effective and more useful for a wide range of missions and easier to produce and launch than their older larger versions and at a fraction of the cost. This is the result of the availability of COTS parts, agile design, lean development techniques, mass production, low cost for parts and the wide spread proliferation of expert knowledge.

Easier accessibility to space is enabling not just universities, smaller countries and research institutions but it is also and especially paving the way for new organizations and startups, to enter the realm of space technologies and space applications. Startups have actually come to lead and dominate the New Space efforts, only to be followed by the older well established space giants and big capital joining an evolving market. The trend has led to a paradigm shift in space technologies and space applications, with the ensuing implications, [65].

5.1. Large Versus Small (Micro and Nano)

Clear advantages of micro and nano satellites over larger ones have been explained above, in terms of cost, size, development time, required infrastructure and expertise. However there are naturally other factors which determine the suitability of one size over the other.
First there are differences in the types of mission requirements, which dictate which size is suitable. Direct Broadcasting Satellites (DBS) at Geosynchronous Earth Orbit (GEO) must necessarily be large because of the power required, large solar energy panels, large antennas, sophisticated electronics and amount of on-board fuel for station keeping over 10-15 years. Their mission cannot be accomplished by smaller LEO satellites, a major reason being the need for fixed direction antennas on the ground.
On the other hand constellations of micro and nanosatellites offer advantages for communications which are difficult for large GEO satellites, as exemplified by such already existing constellations as Iridium [13] and the new initiatives mentioned above, OneWeb, Hiber and SpaceX [17], [20], [14]. Chief among the advantages for micro nano constellations is the difficulty in obtaining a spot at GEO, which is administered by the International Telecommunication Union (ITU). Other factors against larger GEO satellites are the long lead times, high cost, high power requirements for uplinks, signal attenuation at polar latitudes and certain technical/ management difficulties
When it comes to observation of the Earth or the Universe, very high resolution (well below one meter or one micro radian) and precise pointing accuracy requires large telescopes, that is, large mirrors, optics and the subsystems for cooling and precision attitude control, which make them necessarily large and impossible or very hard to implement on micro satellites. That goes for optical imaging such as with Hubble, and certain other scientific satellites looking out to the heavens, as well as the very high submeter resolution required of certain Earth imaging satellites.
Large very high-resolution Earth imaging satellites are expensive requiring sophisticated infrastructure and a rather long time to build. On the other hand, micro and nano satellites may be limited in their resolution to a meter or few meters. However they have other advantages which would be very costly with larger satellites. Since micro and nano satellites are much cheaper than the larger ones, many of them, tens or hundreds, can be flown resulting in revisit times of only a few hours or less than an hour, which give them a great advantage in terms of timely information and proper monitoring. This is no match for the revisit times of a several days of a large very high resolution satellite.
Furthermore, whether for communication or observation, constellations of micro and nano satellites offer unmatched resiliency against loss or malfunction. Losing one or a few from many, does not degrade overall operational effectiveness with a large constellation, whereas losing the only one large super resolution satellite would result in complete failure of the mission. Maintaining large scale constellations however, require special management techniques with logistics approach [65].
Another advantage is that technological upgrades and innovations are easier to implement when a constellation is constantly being upgraded by one or a few micro and nano satellites, as new additions or replacements, every few months or so, which is not possible when only one large satellite is produced and launched every three or more years.

5.2. Debris Problem

Space debris is already a problem of major concern, which is normally expected to be further exacerbated by the thousands of new of micro and nano satellites joining the others. There are now more than 23 000 objects 10 cm or larger in size that are being tracked in LEO with most debris in a belt between 600 and 1200 km above the Earth. There is talk of a Kessler Effect by which collisions may lead to runaway increase in collisions which may render space unusable for many purposes [67] [68].
While it is true that the thousands of nano and micro satellites have the potential to make a significant impact on space debris, there are mitigating efforts, precautions and parameters to adjust. First, their small size or geometric cross section reduces the probability of a collision. In fact it was said that one factor in the original concept of the 10×10×10 cm cubesat was based on the minimum size that the U.S. Air Force publicly acknowledged it could track in LEO.
A measure to reduce the risk of debris increase, is to prevent fragmentation after a collision, that is, to construct a satellite so that it still remains in one piece despite a high speed collision. This may be easier for nano and micro satellites than for larger satellites which are known to defragment into thousands of pieces upon collision at the very high speeds of satellite collisions.
These satellite parameters, ie. being small and sturdy are offset by the sheer numbers. Another precautionary measure for debris prevention is orbit selection and most importantly deorbiting. Most current micro and almost all nanosatellites do not have propulsion subsystems to enable them to maneuver out of problematic areas and to lower the orbit to a naturally decaying one. As the satellite size grows to the minisatellite class and more, inclusion of propulsion systems softens the problem. The last

remaining fuel can be used to reduce the orbit leading to atmospheric reentry.

Orbits below about 500 Km have the feature of natural decay within a few years, limiting satellite life times to short periods if not possessing propulsion subsystems to boost up the orbit. This is not so much of a problem for most nano and micro satellites whose lifetimes are so planned anyway. In any case there are passive ways to hasten the deorbiting at low LEO, already tried by a cubesat by blowing a balloon. For larger more expensive satellites though, such low orbits require propulsion systems, on-board fuel and occasional orbit maneuvers to maintain operation for many years.

There are now deorbit guidelines published by UN COPUOS and some space agencies, which are not mandatory However an increasing number of micro and minisatellites have been trying to comply as much as possible, in orbit selection and design features. If (and when) the debris problem reaches a more serious disturbing level, an international agreement of sorts will be on the international agenda for a space traffic control system. The UN ITU agreement on GEO orbit allocations was actually a first step in the direction of an international regulation on orbit management.

It must also be mentioned at this point that there have been proposals for active debris removal from several countries and institutions including the European Union, US and Japan [69], [70]. However technical, economic and political hurdles have impeded any progress on this front so far.

5.3. Spectum Allocation Problems

Electromagnetic spectrum is a limited natural resource. Frequency demands by large numbers of nano and micro satellites are pressuring spectrum use allocations. Most of the nanosatellites other than the large commercial constellations, use frequencies in the VHF and UHF bands which are already congested. The short lives of most such satellites, which primarily serve research and technology development purposes, are a welcome feature to allow frequency reuse. However still, the problem of spectrum allocation in the lower EM bands will not get any better causing increasing new restrictions.

The demand for bandwidth for the large volume of data from Earth imaging satellites have been met at the X-band so far, under 10 GHz. This is not sufficient for the demands of the large constellations planned by such companies as SpaceX and OneWeb, which require large bandwidths. Therefore these constellations are moving their communications to the Ka band (20-30 GHz) and even V band (35 GHz). However these bands have to be carefully managed to avoid concerns about interference with the GEO satellites. Spectrum allocation is both a technical and a legal issue, under negotiation at international forums like the ITU, [71] [72].

5.4. Economic, policy and Social Issues

Technological developments, including miniaturization and COTS availability of necessary components have made micro and nano satellites a low cost, technically not difficult way of accessing space and opening up new business opportunities to benefit from space applications. These satellites now form a basic and major component of the New Space paradigm, expected to occupy a large segment of the global space market.

It was reported in [3] (Sweeting 2018) that "In the present decade, some 400 emerging space companies have been founded supported by $10 billion in investments, all seeking to deliver new applications or pursue new approaches to operating in space. Strategic investors, wealthy entrepreneurs, and venture capital comprise the largest investment by volume, while angel investors support the greatest number of individual deals."

The year 2019 was predicted to be the year for space by one financial and market company. Other market companies also made similar bright forecasts for the small satellite market for the 2020s [73], [74], [75].

An important feature of the new paradigm is that it is the industry, private sector and startups with venture capital backing, which are leading the new trend. This is different from the traditional scheme, where government agencies have taken the central role in space development. There is also collaboration between university institutions and between small startups and large corporations.

However optimistic predictions will mean well for some but not others. Market conditions will dictate as usual that of the many new initiatives, some will go defunct or leave the field or merge with others. This is already taking place and is expected that the usual trend will continue in the 2020s until only a few successful ones will be left in the latter part of the decade in their respective application areas. It will be mostly conditions in the marketplace. However also government policies which will shape the results.

Developments in space applications in the last two decades have in effect nullified previous policies of many governments in both remote sensing and communications. It used to be before the turn of the century that ground resolution better than 5 or even 10 meters was strictly classified and not publicly available. Then toward the end of the 1990s a US government decision was made to allow private sector companies to launch and operate high resolution imaging satellites and sell the 1 meter or better resolution imagery, at a nominal cost. For a while that decision drew objections from some countries which did not want images of its territory to be made almost freely available worldwide. We have come a long way from such worries of 20 years ago to where 40cm resolution images are now routinely sold. Micro satellites may not reach that resolution, but they are offering something bigger ones cannot, that is revisit times of an hour or even less for close monitoring even at 2-3 meter resolution.

In communications, governments have traditionally tried to control the flow of information to its citizens often banning or jamming foreign broadcasts. One example is the prevention of access to Radio Free Europe in the days of the cold war. Then DBS TV transmissions from space became a means of overcoming the obstruction efforts. When the internet came along, it became a very important way of information dissemination and exchange, which certain authoritarian governments wanted to control. This is relatively easy when terrestrial networks are under government control. However the days are near when any world citizen can directly access a satellite overhead with no government interruption, as will be possible with the constellations of LEO communication satellites as mentioned above.

The New Space paradigm shift, brought in mostly by nano and micro satellites, will thus have implications not just in the space related business or science or security, but also in the general government and societal affairs, as well.

Finally o few words about the Covid 19 epidemic and the ensuing economic crises, which came up after this paper was written and submitted for review. The crises has had quite a negative effect on the space sector as it has on most other sectors, leading to the delays and cancellations of projects as well as more severe cases of closures and banckruptcies as with OneWeb mentioned above. The long term consequences are to be seen as the epidemic developments unfold.

6. REFERENCES

[1] New Space Journal. [Online]. Available: http://www.newspacejournal.com/. [Accessed Feb. 17, 2020]

[2] J. R. Behrens and B. Lal, “Exploring Trends in the Global Small Satellite Ecosystem”, New Space, vol. 7, No. 3, pp. 126-136, September 2019. [Online]. https://doi.org/10.1089/space.2018.0017 [Accessed Sept. 17 2019]

[3] S. Janson, “25 Years of Small Satellites,” in the Aerospace Corp., Small Satellite Conf. 2011, https://digitalcommons.usu.edu/smallsat/2011/all2011/21.

[4] M. Sweeting, “Modern Small Satellites-Changing the Economics of Space”, Proceedings of the IEEE. vol. 106, pp. 343-361, March 2018. [Online]. https://ieeexplore.ieee.org/document/8303876. [Accessed: Jan. 07 2020].

[5] D. N. Bakerand S. P. Worden, “The Large Benefits of Small-Satellite Missions” EOS vol.89, pp. 301-312 August 2008. [Online]. Available:https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008EO330001 [Accessed Dec. 18 2019]

[6] K. Baker “A Brief History of AMSAT”, samsat.org [Online] Available: https://www.amsat.org/amsat-history/ [Accessed Dec. 15 2019].

[7] M. CARCERES, “Rick Fleeter’s Personal Satellite Revolution Has Begun”, Huffington Post June 18, 2014. [Online]. Available: https://www.huffingtonpost.com/marco- caceres/rick-fleeters-personal-sa_b_5175820.html. [Accessed Dec. 18 2019].

[8] R.Fleeter “Current Satellite Programs at AeroAstro”, AeroAstro, Inc. March 27, 2003. [Online]. Avaible: http://satcom.jp/English/english2-3/souryokue.pdf [Accessed Jan.07 2020].

[9] Small Satellite Conference, Utah State Univ. [Online]. Available: www.smallsat.org [Accessed Jan. 15 2020].

[10] Cubesat main ref. [Online]. Available: https://www.cubesat.org [Accessed Dec. 20 2019].

[11] The CubeSat Program, CalPoly SLO, "CubeSat Design Specification" (PDF), Rev 13. [Accesses Jan. 07 2020]

[12] A. S., R. and Xavier Jr., A. (2019), A Unified Satellite Taxonomy Proposal Based on Mass and Size. Advances in Aerospace Science and Technology, vol. 4, pp.57-73. [Online]. Available: doi: 10.4236/aast.2019.44005 [Accessed Dec. 2019].

[13] J. Bloom, Eccentric Orbits: The Iridium Story, London, UK, Grove Press, 2016

[14] SpaceX company website. [Online]. Available: SpaceX.com [Accessed Jan. 07 2020].

[15] C. Henry, “Amazon Planning 3,236 - Satellite Constellation for Internet Connectivity,” space.com, April 5 2019. [Online]. Available https://www.space.com/amazon-plans-3236-satellite-constellation-for-internet.html . [Accessed: Jan. 07 2020]

[16] Amazon working on internet-serving satellite network,April 4, 2019. [Online]. Available: http://www.spacedaily.com/reports/Amazon_working_on_internet-serving_satellite_network_999.html [Accessed: Jan. 5, 2020].

[17] OneWeb satellite company website. [Online]. Available: https://onewebsatellites.com/ [Accessed Feb. 20, 2019].

[18] OneWeb and Airbus start up world’s first high-volume satellite production facility in Florida, Jul. 23 2019. [Online]. Available: http://www.spacedaily.com/reports/OneWeb_and_Airbus_start_up_worlds_first_high_volume_satellite_production_facility_in_Florida_999.html [Accessed: Sept. 25 2019].

[19] Arianespace to orbit the first six satellites of the OneWeb constellation, Kourou, French Guiana (ESA) Feb 20, 2019. [Online]. Available: http://www.spacedaily.com/reports/Arianespace_to_orbit_the_first_six_satellites_of_the_OneWeb_constellation_999.html [Accessed: Jan. 07, 2020].

[20] A. Howe, “Meet Hiber, the Amsterdam space tech startupwants to provide global lot coverage at a low cost,” siliconcanals.com, Oct. 10 2019.[Online]. Available: https://siliconcanals.com/news/meet-hiber-the-amsterdam-space-tech-startup-that-wants-to-provide-global-iot-coverage-at-a-low-cost/ [Accessed: Jan. 13 2020].

[21] Iceye. [Online]. Available: www.iceye.com [Accessed: Jan. 28 2020].

[22] Planet. [Online]. Available: www.planet.com [Accessed: Jan. 28 2020].

[23] Spire. [Online]. Available: www.spire.com [Accessed: Jan. 28 2020].

[24] Pioneer satellites launched, Jul. 9 2019. [Online]. Available:http://www.spacedaily.com/reports/Pioneer_satellites_la unched_999.html [Accessed: Sept. 20 2019].

[25] CUMULOS takes nighttime images of major global cities, May. 27. 2019. [Online]. Available: http://www.spacewar.com/reports/CUMULOS_Takes_Nighttime_Images_of_Major_Global_Cities_999.html [Accessed: Sept. 21 2019].

[26] A. Manning, “Small, nimble CSU satellite has surpassed a year in space” spacedaily.com, Jul. 31, 2019. [Online]. Available: http://www.spacedaily.com/reports/Small_nimble_CSU_satellite_has_surpassed_a_year_in_space_999.html. [Accessed: Dec. 15 2019].

[27] B.Hays,”New nano-satellite system yields high-res imagery at lower cost” spacewar.com, Jan 4, 2019. [Online]. Available: http://www.spacewar.com/reports/New_nano-satellite_system_yields_high-res_imagery_at_lower_cost_999.html [Accessed: Sept. 17 2019].

[28] CubeSats prove their worth for scientific missions, Apr 17, 2019. [Online]. Available: http://www.spacedaily.com/reports/CubeSats_prove_their_worth_for_scientific_missions_999.html [Accessed: Sept. 17 2019].

[29] NASA cubesat mission page. [Online] sss https://www.nasa.gov/mission_pages/cubesats/index.html.

[30] NASA flies seven student cubesats https://www.nasa.gov/wallops/2019/feature/seven-student-made-cubesats-set-to-fly-aboard-antares-nov-2-from-wallops.

[31] CIRIS mission launched, https://www.nasa.gov/feature/goddard/2019/new-nasa-funded-cubesat-poised-to-take-earth-s-temperature-from-space

[32] Small satellites key to NASA's lunar search for water, http://www.moondaily.com/reports/Small_satellites_key_to_NASAs_lunar_search_for_water_999.html.

[33] NASA Small satellite concept finalists target Moon, Mars and beyond Pasadena CA (JPL) Jun 21, 2019. [Online]. http://www.spacedaily.com/reports/Small_satellite_concept_finalists_target_Moon_Mars_and_beyond_999.html?mc_cid=57906eb5a8&mc_eid=752a89461f. [Accessed Sept. 17 2019].

[34] T. Abate, Stanford and NASA Ames researchers put inexpensive chip-size satellites into orbit, Stanford News, Jun 06, 19. [Online]. Available: http://www.spacedaily.com/reports/Stanford_and_NASA_Ames_researchers_put_inexpensive_chip_size_satellites_into_orbit_999.html [Accessed: Sept. 20 2019].

[35] Student satellite deployed from ISS, Jul. 23 2019. [Online]. Available: http://www.spacedaily.com/reports/Student_built_satellites_deployed_into_orbit_from_the_International_Space_Station_999.html. [Accessed: Sept. 20 2019].

[36] J. Green, Satellite built by Virginia Tech undergraduates ready for launch into space VT News, Blacksburg VA Apr 16, 2019. [Online]. Available: http://www.spacedaily.com/reports/Satellite_built_by_Virginia_Tech_undergraduates_ready_for_launch_into_space_999.html [Accessed: Jan. 28 2020].

[37] Smallsat integrated K Ka band transceiver. Aug 5 2019 [Online]. Available: http://www.spacedaily.com/reports/Arralis_launches_smallsat_integrated_low_profile_K_Ka_Band_Transceiver_999.html [Accessed: Jan. 20 2020].

[38] ESA on cubesat technology. [Online]. Available: https://www.esa.int/our_activities/space_engineering_technology/technology_cubesats [Accessed: Jan. 28 2020].

[39] ESA supporting cubesats. [Online]. Available: http://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_CubeSats [Accessed: Jan. 28 2020].

[40] ESA: Cubesat central for small missions. [Online]. Available: http://www.spacedaily.com/reports/ESAs_Cubesat_central_for_smaller_missions_into_space_999.html [Accessed: Sept. 17 2019].

[41] ESA, Earth observations. [Online]. Available: http://www.esa.int/Applications/Observing_the_Earth [Accessed Jan. 7 2020].

[42] ESA Support operations. [Online]. Available: http://www.esa.int/Enabling_Support/Operations [Accessed: Jan. 7 2020].

[43] CubeSats joining Hera mission to asteroid system, Paris (ESA) Jan 08, 2019. [Online]. Available: http://www.spacedaily.com/reports/CubeSats_joining_Hera_mission_to_asteroid_system_999.html. [Accessed: Sept. 17 2019].

[44] Gomspace: [Online]. Available: https://gomspace.com. [Accessed: Jan. 7 2020].

[45] Gomspace, Lockheed and Orbital Micro team up for microwave sensing nanosatellite project. [Online]. Available: http://www.spacedaily.com/reports/GomSpace_Lockheed_Martin_Space_and_Orbital_Micro_Systems_team_up_for_new_microwave_sensing_nanosatellite_project_999.html [Accessed: Jan. 22 2020].

[46] Sandbox satellite to test operations innovations in space. [Online]. Available: http://www.spacedaily.com/reports/Sandbox_satellite_to_test_operations_innovations_in_space_999.html [Accessed: Jan. 22 2020].

[47] Successful satellite launch for Graz Universty of Technology, Austria. Dec. 19, 2019. [Online]. Available: http://www.spacedaily.com/reports/Successful_satellite_launch_for_Graz_University_of_Tecnology_Austria_999.html [Accessed: Jan. 22 2020].

[48] Surrey Satellite Technology, UK. [Online]. Available: www.sstl.co.uk [Accessed: Jan. 22 2020].

[49] Leading the New Space Age: Government backs ambitious plans for the UK in space, Jun. 06, 2019. [Online]. Available:http://www.spacedaily.com/reports/Leading_the_New_Space_Age_Government_backs_ambitious_plans_for_the_UK_in_space_999.html [Accessed: Jan. 28 2020].

[50] UK spaceport at Cornwall. [Online]. Available: https://spaceportcornwall.com [Accessed: Jan. 28 2020].

[51] UK’s solar science mission using cubesats. [Online]. Available: http://www.spacedaily.com/reports/UK_led_solar_science_mission_to_use_cubesats_999.html [Accessed: Jan. 22 2020].

[52] Oxford Space Systems. [Online]. Available: https://oxford.space/ [Accessed: Jan. 28 2020].

[53] SSTL and OSS Collaborate on Disruptive Smallsat SAR Payload, Guildford UK Apr 04, 2019. [Online]. Available: http://www.spacedaily.com/reports/SSTL_and_OSS_Collaborate_on_Disruptive_Smallsat_SAR_Payload_999.html [Accessed: Jan 22 2020].

[54] Space Flight Laboratory Reaches Century Milestone in Microspace Operations, Apr 16, 2019. [Online]. Available: http://www.spacedaily.com/reports/Space_Flight_Laboratory_Reaches_Century_Milestone_in_Microspace_Operations_999.html [Accessed: Jan. 7 2020].

[55] Space Flight Laboratory and Kepler Communications team up for nanosatellite constellation, Microsat Blitz, micro and nano satellite news, Feb. 06, 2020. [Online]. Available: http://www.spacedaily.com/reports/Space_Flight_Laboratory_and_Kepler_Communications_announce_collaboration_on_fully_operational_nanosatellite_constellation_999.html [Accessed: Feb. 24 2020].

[56] Aslan, Alim Rustem, Y. Ozyıldırım, Alime et.al, First High Resolution High Speed CubeSat of Turkey Joint Conference: 31stISTS, 26thISSFD & 8thNSAT, Matsuyama-Ehime, Japan, June 3-9, 2017.

[57] AR Aslan, HMK AlNaimiy, I Fernini, A Manousakis, M Shaikh, SR Madara, et.al,” Space Technology Capacity Building in Support of SDG 2030 Through CubeSat SharjahSat-l, 9th International Conference on Recent Advances in Space Technologies, RAST2019, Istanbul, 11-14 June 2019.

[58] R. J. Bonometti, E. D. Nicastri, "The role of small satellites in our national defense", Advanced Space Technology Program Defense Advanced Research Projects Agency. [Online] Available: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2557&context=smallsat. [Accessed: Jan. 27 2020].

[59] Nato embraces for the new space policy. [Online]. Available: https://www.euractiv.com/section/global-europe/news/nato-braces-for-the-new-space-age/ [Accessed: Jan. 21 2020].

[60] NATO's new space policy. [Online]. Available: https://www.euractiv.com/topics/space-policy/ [Accessed: Feb. 17 2020].

[61] US developing cheap, disposable spy satellites from civilian tech, Washington DC (Sputnik) Aug 31, 2018. [Online]. Available: http://www.spacewar.com/reports/US_developing_cheap_disposable_spy_satellites_from_civilian_tech_999.html [Accessed: Aug. 17 2019].

[62] We are shrinking the telescope: An up-close look at SPIDER. [Online]. Available https://www.lockheedmartin.com/en-us/news/features/2016/webt-spider.html [Accessed: Dec. 18 2019].

[63] USAF Pearl White cubesats mission set to launch. Mahia, New Zeland, Aug 9, 2019. [Online]. Available: http://www.spacedaily.com/reports/Pearl_White_cubesats_mission_set_to_launch_999.html. [Accessed: Dec. 17 2019].

[64] A. Das and R. Cobb, Space Missions using Collaborating Constellations of Satellites, Air Force Research Laboratory. [Online]. Available https://digitalcommons.usu.edu/smallsat/1998/all1998/31/ [Accessed: Jan. 17 2020].

[65] M. Wallace. "Meet the big-thinking space startups that want to transform the universe with tiny satellites", Fastcompany, 05-04-2019. [Online]. Available: https://www.fastcompany.com/90343269/how-small-satellites-and-rapid-launch-could-transform-the-business-of-space. [Accessed: Dec. 4 2019].

[66] Maintaining large scale satellite communications usinglogistics approach. [Online]. Available: http://www.spacedaily.com/reports/Maintaining_large_scale_satellite_constellations_using_logistics_approach_999.html. [Accessed: Dec. 4 2019].

[67] US Space Surveillance Network. [Online]. Available: https://en.wikipedia.org/wiki/United_States_Space_Surveillance_Network. [Dec. 16 2019]

[68] ESA Space Debris site. [Online]. Available: https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers. [Accessed: Feb. 17 2020].

[69] J. N. Pelton, "A path forward to better space security: Finding new solutions to space debris, space situational awareness and space traffic management", Journal of Space Safety Engineering, vol. 6, Issue 2, Pp. 92-100, June 2019.

[70] Astroscale awarded grant From to commercialize active debris removal services, Tokyo, Japan, Jan 24 2020. [Online]. Available: http://www.spacedaily.com/reports/Astroscale_awarded_grant_From_to_commercialize_active_debris_removal_services_999.html. [Accessed: Jan. 27 2020].

[71] P. Larsen, "Small Satellite Legal Issues", 82 J. Air L. & Com. 275 (2017).

[72] J. Alvarez and B.Walls, "Constellations, clusters, and communication technology: Expanding small satellite access to space", 2016 IEEE Aerospace Conference, IEEE, 5-12 March, Big Sky, USA. [Online]. Available: https://ieeexplore.ieee.org/document/7500896 [Accessed: May 18 2019]

[73] Morgan Stanley says 2019 could 'be the year for space,' led by the likes of SpaceX and Blue Origin, NOV 28 2018.[Online]. Available: https://www.cnbc.com/2018/11/28/morgan-stanley-says-2019-could-be-the-year-for-space.html [Accessed Jan. 7 2020].

[74] Small Satellites Flying High with $37 Billion Market and 6,500 Satellites to Launch by 2027 NSR November 28, 2018. [Online]. Available: https://www.apnews.com/1ce35eb63721cadb084b97f85f18f191 [Accessed Jan. 8 2020].

[75] Small Satellite Market, Global Forecast 2020-2025, published Jan 2020, https://www.marketresearchengine.com/small-satellite-market [Accessed Jan. 7 2020]

[76] Tempest. [Online]. Available: https://tempest.colostate.edu/. [Accessed: Jan. 28 2020].

VITAE

Fuat INCE received his BS degree in Electrical Engineering from Bogaziçi University, Istanbul, Turkey, MS and PhD degrees from University of Illinois, Urbana-Champaign, Ill USA, also in electrical engineering. He worked as research engineer, senior research scientist, chief research scientist, and vice president at TUBITAK Marmara Research Center. (TUBITAK is the Scientific and Technological Research Council of Turkey) and later as the Founding Director of TUBITAK's Informatics Research Institute. After 16 years at TUBİTAK, he moved to the private sector to the position of Director of Information Systems at a defense electronics company Savronik, where he served for five years. He then went back to the academic World, became professor and Head of Computer Science and Engineering at Marmara University in Istanbul, Turkey. While at Marmara University and afterwards he also taught computer science and space studies courses at the Turkish Air Force Academy, Aeronautics and Space Technologies Institute, where he helped set up the curriculum of the space studies department. Professor Ince has served in several national and international forums including UN COPUOS and NATO IST Panel. He is a Life Senior member of IEEE and has numerous publications in related fields.