The search for exoplanets is one of the most exciting space science endeavours and though NASA’s James Webb telescope will cost about US$9 billion it may be too small to yield clear scientific conclusions on exoplanets.

To deploy a telescope with double the aperture of James Webb would impose an estimated cost increase to US$36 billion. Such monumental and ultimately unsustainable costs emerge from current concepts in spacecraft design and manufacturing, principally based on the need to fully assemble objects on the ground before launch.

Ground assembly and integration into a launch vehicle imposes significant limitations on the
size, volume and design of payloads that can be accommodated within the fairing of a single launch vehicle, the largest of which is less than six metres in diameter.

In particular, fairing diameter limitations restrict the size and number of instruments that can be fielded in orbit for science and national security missions which, in turn, constrain data that can be obtained from space-borne payloads.

Design of ground built spacecraft also requires components to undergo ‘ruggedization’ to withstand the harsh launch environment - severe vibration, acoustics, acceleration and thermal loads - which imposes mass and size penalties that ultimately limit payload capabilities and increase launch costs.

These are further compounded by the need for inclusion of redundant systems to provide contingency against damage during launch.

Communication satellites have similar constraints that limit flexibility and operations, and Figure 1 illustrates how these affect profitability and revenues.

On-orbit assembly can be defined as the aggregation onto an orbiting platform of ready-made structures that are manufactured on the ground (although they could also be manufactured on-orbit) and here we examine the potential implications of on-orbit assembly of science, exploration and commercial communication spacecraft for science and exploration and, and review the state of the art and future trends in the area.

**Benefits of on-orbit assembly**

At a conceptual level, on-orbit assembly offers a number of advantages that may enable and enhance various types of space missions:

- An ability to deploy structures that cannot be launched from Earth because
of constraints imposed by launch vehicle fairing size and shape. The structures are packaged more efficiently into the launch fairing than can be accomplished with a fully integrated spacecraft

- An ability to achieve increased flexibility and resilience of spacecraft assets enabled by assembly involving additions, replacements and technology updates of payloads onto a compliant, orbiting platform
- An ability to create cost savings related to carrying more useful mass – less packaging material (structure) for ruggedization, and less platform material
- An ability to create cost savings through reduction in the number and intensity of ground-based tests of space-bound spacecraft and subsystems
- An ability to create structures that cannot be created on Earth at all because of constraints imposed by the terrestrial gravity.

These advantages, in turn, can provide dramatic benefits in a number of different ways to a variety of different space operations.

In astronomy, on-orbit assembly can enable the construction of telescopes too large to be fully built on Earth and launched into orbit. High definition space telescopes (HDST) are very large, space-based observatories with a number of primary missions, including characterisation of exoplanets and the search for life on exoEarths through the use of spectroscopic bio-markers.

An analysis performed by the Association of Universities for Research in Astronomy (‘From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy’, 2015) showed that at least 30 candidates must be characterised in order to infer statistically meaningful conclusions about the prospects for biological life on other planets.

The same analysis revealed that telescope aperture diameter is the most important parameter in determining the number of candidates that can be characterised, and the relation is plotted in Figure 2. Data points are included for the Hubble Space Telescope (HST) and for the James Webb Space Telescope (JWST), the latter being the next NASA HDST mission planned for launch in 2018. With an aperture diameter of 6.5 m, it is estimated that JWST will identify about 10 exoEarths.

To advance the search for exoEarth candidates beyond JWST to a level of stronger scientific rigour, a significant increase in telescope aperture diameter is required on future HDST missions and Figure 2 shows that an aperture of 12 m would yield more than 30 candidates.

The JWST aperture is approaching the size limit for what can be accommodated within current launch vehicle fairings; even then, this size necessitates use of a complicated folding arrangement, with many associated risks and ground testing requirements.

While larger launch fairings are being considered in the development of future launch systems, significant growth beyond current capabilities is both technically challenging and extraordinarily expensive.

The idea is to assemble a large telescope in space using large hexagonal elements that are 4m across from one flat side to another.
On-orbit assembly provides a potential pathway to address the size challenges of next generation HDSTs. For example, consider the three-stage evolvable space telescope concept described in Polidan et al., (Proceedings of SPIE, 9143, 2014) and shown schematically in Figure 3.

The idea is to assemble a large telescope in space using hexagonal elements that are 4 m across from one flat side to another. The telescope would evolve over three launches that are separated by budget cycles spread over several years. In the first stage, the central circular secondary mirror, and two hexagon elements that form the primary mirror assembly (PMA) are launched in a single stack and assembled on-orbit to form an asymmetric aperture of 4.5 m x 12 m.

In the second stage, four additional hexagon elements are launched in a single stack, and assembled to form a symmetric aperture of diameter 12 m. The third stage launches 12 additional hexagons that would be added to the existing structure to complete a telescope with an aperture diameter of 20 m. The exoplanet yields provided by the three stages are indicated in Figure 2.

In addition to enabling a scientifically important increase in information return for HDSTs by making it possible to evolve the construction of the telescope over multiple years, on-orbit assembly would likely provide significant cost savings.

For Earth science, on-orbit assembly can reduce the number of satellite launches for weather and climate observations through the creation of a persistent platform assembled in space. One illustration is the ability to use the persistent platform to replace the A-Train series of satellites that pass over the same spot on the Earth within a few minutes of each other collecting a variety of measurements. Sensors could be added to the platform regularly, enabling faster refresh than is currently feasible. Just as importantly, assembly of multiple payloads (as well as refresh) onto one platform would require fewer launches, and provide launch savings of several hundred million dollars.

**Communications satellites**

On-orbit assembly can also provide payoff for telecommunications in geostationary orbit (GEO).
Consider the data distribution sector where the satellite is used to move data from one central location to other regions of the world. Take a communications satellite with four antennas that allow it to distribute data to four different regions simultaneously. Due to the dynamic nature of end-user data distribution requests, these satellite systems typically achieve utilisation rates of only 60 to 70 percent. An increase in the number of antennas, without changing any other part of the satellite, would allow use to increase.

For illustration, we assume that increasing the number of antennas from four to eight would increase utilisation efficiency by 10 percent. The antennas are not assembled onto the spacecraft prior to launch but rather are packed efficiently into the fairing above the satellite platform. Once in orbit, the antennas are assembled robotically onto the satellite before transfer to GEO.

Assuming the satellite generates revenue at a rate of US$1.5 million per transponder per year (the recent historical average), a typical number of 36 transponders on the satellite, and a 10 percent increase in utilisation due to the use of on-orbit assembly to double the number of antennas from four to eight, the total increase in revenue would be US$5.4 million per year. Over the 15-year lifetime of a typical satellite, this yields a total revenue increase of US$81 million.

Another important limitation of communications satellites fully assembled on the ground is that once deployed on orbit, the technological capabilities remain fixed for the lifetime of the spacecraft. This is an important consideration since the lifetime of most GEO satellites is 15 years.

The ability to reconfigure a telecommunications satellite through on-orbit re-assembly could provide valuable capability upgrades for operators, that may be especially important as GEO operators begin to gear up to compete with low Earth orbit (LEO) constellations expected to see refresh rates as low as 18 months.

The revenue generated by a communications satellite depends primarily on the rate at which information can be moved through the system, measured in bits per second. Similar to Moore’s Law for computer processor speed, the historical data for the evolution of satellite bit-rate shows a predictable upward trend with no end in sight. Specifically, the bit-rate has been seen to increase by a factor of 10 every seven years or so.

When a new satellite is launched, in its first year of operation it provides the fastest bit-rate available in the market. However, each year that passes sees new satellites placed into orbit with a performance that exceeds that of the older asset. Thus, a seven-year old satellite is operating at a bit-rate that is a factor of 10 slower than the newest satellites in operation.

Now consider the situation in which on-orbit assembly makes it possible to replace the entire communications payload on the satellite after seven years of operation. The new payload would refresh the technology and instantly increase the bit-rate of the asset. As an illustration, we again assume the satellite generates revenue at a rate of US$1.5 million per transponder per year, and 36 transponders on the satellite. We will further assume a factor of 10 increase in bit-rate enabled by on-orbit assembly of the updated communications payload.

However, this improved performance will be accompanied by a reduction in customer charge rate, and for our analysis we assume that the charge rate decreases by a factor of five. The cost of the second launch is assumed to be US$40 million and that of the new communications payload is estimated at US$100 million. Figure 4 shows the accumulation of revenue over the operational lifetime of the satellite under the current paradigm and for the new approach in which the technology is refreshed after seven years. The total revenue...
increase at end of life enabled by on-orbit assembly is about US$300 million per satellite.

Figure 5 shows how assembling more antennas onto a single platform, conducting on-orbit manufacture and assembly to eliminate the stresses of launch, and assembling refreshed payloads onto an existing platform, all contribute to increased system performance and revenue return for a communications satellite.

Technical capability status
Having identified the potential benefits of on-orbit assembly, it is informative to review present status and future prospects for the technical capabilities that can be expected. On-orbit assembly of spacecraft will require development of a number of technologies and processes involving sensing, robotics, automation and modular interfaces between payloads and platforms.

Relevant space activities that represent intermediate steps to full on-orbit assembly include on-orbit inspection and servicing of spacecraft. A significant heritage has been built up over the last 50 years by astronauts conducting on-orbit assembly and lessons learned from these activities will inform future missions and the development of new techniques.

Capabilities are being developed for automated on-orbit inspection of spacecraft. In the United States, the Air Force Research Laboratory (AFRL) Automated Navigation and Guidance Experiment for Local Space (ANGELS) spacecraft investigated technologies and procedures for maneuvering and imaging within a few kilometres of an expended rocket body.

Concepts are also being developed using sensors for inspection of spacecraft. On-orbit servicing, including autonomous docking, was demonstrated by the US Defense Advanced Research Projects Agency’s (DARPA) Orbital Express in 2007. The mission involved a surrogate next generation satellite and a prototype servicing spacecraft. The satellites docked several times, and the prototype servicer refuelled the satellite and exchanged modules.

The most impressive example of astronaut-assisted assembly is the construction of the International Space Station (ISS), which involved over 35 Space Shuttle launches and 160 spacewalks spanning 1,061 hours. The station is the size of a football field weighing over 400,000 kg and encompassing over 900 cubic metres of pressurised volume, and has been called home by over 200 people representing 15 countries.

Robotic assembly
A spectrum of robotic assembly techniques could be used to replace astronaut assembly, from robots as eyes, subordinates and sidekicks to robots as surrogates and specialists.

United States’ Orbital ATK’s Mission Extension Vehicle (MEV) is one example of a servicing capability. The NASA Restore-L mission is scheduled for 2020, and involves the refuelling of Landsat-7 by a MEV. The MEV will autonomously rendezvous with the Landsat spacecraft and then tele-robotically cut wires, remove caps and refuel the satellite. Landsat-7, an unprepared ‘client’ built long before MEV technology was available, will be about 20 years old at that point.

Restore-L demonstrates the potential for robotic servicing to increase the lifespan and safety of current missions. The Space Dynamics Department of Germany’s Institute of Robotics and Mechatronics runs a mission called Deutsche Orbitale Servicing (DEOS) which involves two satellites, a ‘client’ and a ‘servicer’. Planned to launch in 2018, the servicer will chase and rendezvous with the client, demonstrate refuelling and module exchange, and then safely de-orbit the client.

DARPA is developing robotic servicing vehicles for GEO satellites as part of its Robotic Servicing of Geosynchronous Satellites (RSGS) project. Satellites in this high orbit will be able to be repaired and maintained over time, increasing their capabilities and value to their owners. Under development since 2016, the planned launch date is 2021.
On-orbit assembly has the potential to radically change the way in which spacecraft are deployed for a number of important space missions

In early 2016, ESA flew the Intermediate Experimental Vehicle (IXV); in 2020 it is expected to fly the Program for a Reusable In-orbit Demonstrator from Europe (PRIDE). IXV demonstrated many key capabilities for on-orbit maneuverability; PRIDE will provide a platform for the experimentation with and development of on-orbit servicing capabilities.

Self-assembly, which involves small satellites with specialised capabilities self-organising to fulfill the objectives of a larger mission, is enabled by advances in formation flight. DARPA is pursuing the Phoenix Satlet concept whereby small autonomous modules incorporate key satellite capabilities and aggregate in various combinations to achieve different mission goals. The modularity of the Satlets increases mission resilience and re-configurability, reduces spacecraft design and integration time, and provides cheaper redundancies. In tandem with the Payload Orbital Delivery (POD) system, deployment costs are reduced. Satlets have been under development since 2012, and the first LEO flight is planned for 2017.

Operational challenges

Many on-orbit assembly capabilities face space environment challenges, such as microgravity, atomic oxygen (in LEO), radiation and micrometeoroid impacts. It may therefore be necessary to deploy a protective shell structure in orbit, in which assembly can proceed free from many of these environmental concerns. For LEO operations, there is also the continual significant variation in the lighting environment caused by going in and out of eclipse, which may negatively impact vision-based operations. Tele-robotic missions are impacted by communication latencies and therefore require tasks such as rendezvous and docking to be entirely automated. When not supervised by an astronaut, on-orbit assembly requires a robotic system with high reliability and a high degree of ‘trust’ between human and robot. New operational steps must be developed to verify that the assembly procedures have been executed as planned.

Some of the challenges faced by robotic, autonomous on-orbit assembly can be addressed by learning and benefiting from the much more extensive worldwide activities of terrestrial-based applications of the same technologies. Use of automated, robotic assembly of complex machines is widespread and growing in capability on the ground across many industries. Important examples include large industries such as automotive and micro-electronics, as well as assembly of components directly related to spacecraft such as antennas and solar-cells.

Future impact

On-orbit assembly has the potential to radically change the way in which spacecraft are deployed for many important space missions. The already long history of astronaut-assisted on-orbit assembly combined with ongoing progress in on-orbit inspection and servicing will have a significant impact on on-orbit assembly in the next decade, especially if the space sector is able to leverage investment in terrestrial activities in robotics and automation.

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