Watching the world go by

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ABSTRACT

The Carbonite-1 and -2 microsatellites launched in 2015 and 2018 are delivering high-resolution, high-definition colour video from space, providing a new dimension to Earth Observation and "big data" analytics. Single video imaging spacecraft have limited utility. In order to fully benefit from such spacecraft requires cost-effective observations with multiple opportunities per target per day, driving the need for large-scale constellations of ultra-low cost spacecraft. The first constellation based on the two pilot missions is now in production, and will start commercial operation by 2020. Still-imagery has a number of limitations in applications related to surveillance, disaster monitoring and news gathering. Video can provide additional contextual information, and space borne video systems have been demonstrated several times over the past decades. Single video imaging spacecraft in LEO are limited in application, as they cannot cover specific target areas on the globe frequently enough. Furthermore, previous video imaging missions have generally lacked the necessary resolution to allow fine scale human activity to be monitored, such as traffic and crowds.

INTRODUCTION

The current trend in the Earth Observation (EO) market is on deploying and operating large constellations of small satellite platforms. This is driven by the need to provide high temporal resolution in order to enable downstream market applications that require frequent revisits. However, this requires reliable satellites that are designed for mass-manufacturability, shared launch, and automated operations in order to reduce cost and schedule.

At the same time as providing high utility with increased revisit, there is a need to provide high-resolution imagery with high fidelity. Traditionally, these classes of satellites have typically been large, costly, and often built one at a time. However, the "smallsat mentality" has pushed the performance envelope of small satellites thereby enabling high capabilities that until a few years ago could only be found in satellites costing ten or twenty times more.

Over the last 30 years, Surrey Satellite Technology Ltd. (SSTL) has been at the forefront of small satellite design and innovation. With 55 small satellites launched, ranging in applications from Earth Observation, Communications, Navigation, Science and Technology Demonstrations, SSTL has gained invaluable experience using a flexible design approach and rapid development thereby delivering reliable satellite missions at low-cost and within short timescales.

As the market moves towards small satellite constellations, demand for low-cost and reliable spacecraft, by themselves or in groups, has therefore been increasing. SSTL, building on experience gained in small satellite and constellation business, has developed a series of spacecraft to meet the needs of this expanding market and launched Carbonite-1 in July 2015. The "smallsat mentality" was applied with the mind-set of reducing schedule and cost in order to enable a high utility imaging and video mission and that is highly suited for emerging large constellation EO programs. The first generation satellite was developed and built in six months, with Carbonite-2 mission due for launch in 2017, and with future iterations are planned for delivery within three months.

VIDEO IMAGING APPLICATIONS

Video imaging has a range of possible civil, security and commercial applications, but limitations in capability have previously made it difficult to implement operationally useful systems. There have been a few demonstrations of video imaging capability most notable on the TUBSAT series of missions, and more recently from the space station by Urthecast.

Video imaging can support a range of potential applications. These include:-

- News and media
- Loss adjustment / insurance
- Disaster response
- Data and Economic Analytics
- Smart city management
- 3D mapping
- Cloud avoidance imaging
- Surveillance
    - Maritime
    - Border
    - Environmental
    - Moving target indication
    - Search and Rescue
    - Illegal fishing

Figure 1: Cloud avoidance using video imaging [13]

In recent years, some of the image sensor and small satellite technology has improved to the level where video imaging missions are becoming feasible. Furthermore, cloud computing is making image/video processing viable even with minimal hardware.

Firstly, video imaging is generally only of interest if the resolution is good enough. For most applications this means that very high resolution (metric scale of better) is required. This poses challenges on the spacecraft in terms of instrument size, platform attitude stability, and geolocation.

Secondly, most applications for video require regular revisit to a particular location. Daily opportunities are probably a minimum requirement, and multiple opportunities per day support a much wider range of applications. As such,

Finally, there is no existing market for video imaging, and this would need to be developed. That means that the infrastructure cost (CAPEX) of the satellite constellation, and hence the individual cost of the satellites must be minimal in order to build a suitable business case.

Previous Video Mission

Although there have been a number of video imaging mission launched over the past decade, few comprehensive results have been published other than for the TUBSAT series of missions [4]. Also some video product results from Skybox [6] and Jilin-1 [7,8] have been published. Most recently, SSTL and its customer Earth-i has published videos and application notes from the Carbonite series of spacecraft [11-13]. The table below provides an overview of previous and planned missions. Skybox, BlackSky, Jilin, Zhuhai and Earth-i are all part of planned video imaging constellations

Table 1: Video Imaging missions

Mission	Mass/kg	A4	Launch	GSD/m
TUBSAT-DLR	45	TUB, Germany	‘99	6, 200
MAROC-TUBSAT	47	TUB, Germany	‘01	6, 200
Micron	66	KB Yuzhnoye, Ukraine	‘04	?
LAPAN-TUBSAT	56	TUB, Germany	‘07	6, 200
SkySat-1 (and 2-8)	90	Skybox (Planet), USA	‘13	1
Tantuo-2	67	NUTD, China	‘14	?
Carbonite-1	90	SSTL, UK	‘15	1.4
Ling Qiao 1&2	135	Tsinghua Uni / Xinwei Telecom	‘15	5
Jilin-1, 7, 8	420	CAST, China	’15-18	1.3
ISS “Iris” attached payload	n/a	Urthecast, Canada	‘15	1
Zhuhai-1-4, OVS-2	50-90	Zhuhai Orbita Control, China	’17-18	2
CESAT-1	50	Canon, Japan	‘17	1
Carbonite-2	100	SSTL, UK	‘18	1
NEMO-HD	65	UTIAS, Canada	(‘18)	2.5
Earth-i [9]	90	Earth-i, UK	(‘20)	1
BlackSky constellation [10]	90	SpaceFlight, USA	(‘18)	1
EarthNow [15]	150?	EarthNow LLC	(’20?)	1?

In all cases the video imaging capability is achieved through the use of CMOS area sensors, and although good resolution is achieved, swath width and consequently scene size is limited by sensor technology.

Another approach for high resolution video imaging that has been considered is to place a spacecraft in Geostationary orbit with video imaging capability. That would allow almost permanent imaging of specific selected areas, or rapid panning between different areas of interest. Due to the significantly higher altitude, such a spacecraft would be quite large due to the size of the required instrument. The spacecraft would also need to be designed for a much harsher environment, but could potentially have a longer lifetime if standard geostationary platform technologies are used. This type of system has been proposed by the Airbus group under the GO3S project name for defence, security and environment applications.

The Power of Constellations

SSTL has investigated a number of configurations for video imaging applications, each delivering specific unique requirements leading to different constellation configurations.

For polar sun-synchronous orbits, a string-of-pearls constellations will give at least a single daily imaging opportunities anywhere on the globe, and more at higher latitudes. Each additional plane can then provide another opportunity for the same target at a different time of day.

For exclusive coverage at lower latitudes, for instance 33 degrees, a constellation of 6 satellites spread across two or more planes can provide up to 10 opportunities for a given target every day. Even modest constellations of 24 satellites could provide almost 40 imaging opportunities per day.

An example of a constellation that provides regular daily opportunities for a specific geographic region is shown in Figure 1, with another example that offers multiple repeated opportunities over a specific geographic region shown in Figure 3 [5].

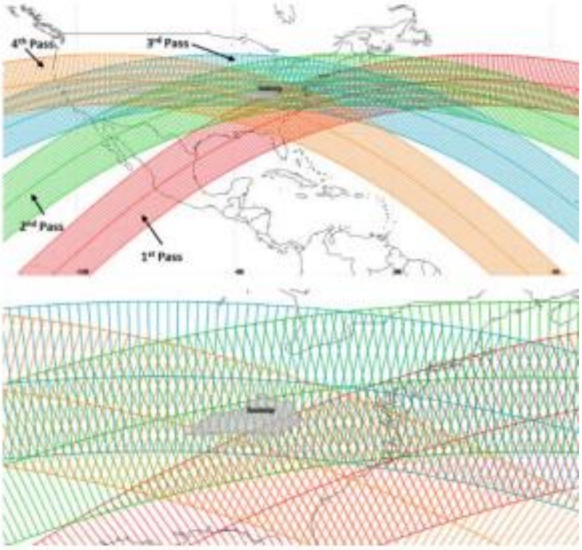

Figure 3: One of the possible constellation scenarios

It is also possible to configure satellites in such a way to provide prolonged video imaging, where one satellite hands over to the next satellite. Some of these configurations tabulated in more detail below:-

Table 2: Constellation Configurations

Scenario	# Satellites	# Orbital planes	Lat 20° revisits per day	Lat 50° revisits per day	Maximum video (minutes)	Average video (minutes)
"Daily opportunities"	5	1	1	1	2.5	2
"several daily opportunities"	12	3	0-2	2-3	2.5	2
"30min intervals"	24	3	3-5	4-6	4.6	3.3
"Prolonged observation"	36	3	1	1	25	15
"regular intervals"	36	4	2	1	19	5
"Prolonged observation"	72	3	>1	>1	52	35
"Prolonged observation"	135	3	1-2	1-3	96	50
"Dedicated and focused observation"	163	9	Multiple	Multiple	264	n/a
"constant surveillance"	484	22	2 minute global revisit [5]			

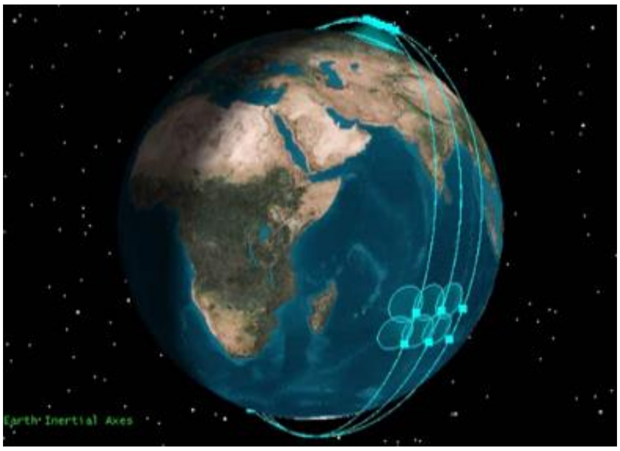

Figure 1: Video Constellation Concept

Considering the fact that large numbers of satellites are required for more interesting video imaging applications, and that the resolution of the video needs to be good enough to observe human scale activity, a small, ultra-low high-resolution imaging spacecraft is required to address these applications at a very low-cost-per-spacecraft. The SSTL Carbonite series of spacecraft missions aims to address these video imaging constellation applications, and forms the basis of a number of different constellation configurations addressing distinct applications.

Carbonite-1 Mission

Carbonite-1 was the 1st generation satellite on a roadmap to develop a new product at a low price point to deliver high resolution imagery and video within a shortened delivery schedule. Launched with the Disaster Monitoring Constellation-3 (DMC3) on the 15th of July 2015, the satellite has been operational since and has demonstrated the rapid response capability of SSTL.

The DMC3 constellation, based on the SSTL-300 S1 platform (the "SSTL S1"), offers a high fidelity performance solution for EO constellations as demonstrated by the cost effectiveness of the mission [1]. Given the size and cost per unit of the SSTL S1, these satellites are optimal for constellations of 3 to 6 satellites, offering high quality / high fidelity imaging capability.

The limitation of such constellations is their temporal resolution, limited to 1 to 3 imaging opportunities per day. For higher temporal resolutions, particularly for the use of video imaging, it is desirable to have constellations that offer multiple imaging opportunities every day. Numbers in the order of 10s of satellite are required, posing a challenge to the satellite designers to reduce the cost of each unit. Only in this way will such constellations be commercially successful.

In 2014, based on earlier studies, SSTL decided to build a prototype, very low cost, high resolution satellite as an in-house technology demonstrator mission. This would become the leading satellite in a new class of in-orbit demonstrator missions aimed at trialling new advanced concepts for use in future missions. Though the Carbonite-1 mission followed a different design philosophy in comparison to the DMC3 constellation, both missions provide high resolution imagery. Carbonite-1 was also designed to demonstrate rapid-build techniques and to test commercial-off-the-shelf (COTS) components and new avionics in orbit.

To keep costs to a minimum and to make use of an existing launch opportunity, the satellite had to be developed and built in six months. The decision to start was taken on the 1st July 2014 and the satellite manufacture was completed on 12th January 2015. This was followed by nearly two months of environmental testing, with the satellite ready to launch within eight months from start.

Figure 4: DMC3 and Carbonite-1 satellites in shared PSLV-XL launch

The overall design philosophy and management approach followed, allowed the mission to be built, tested, and delivered in such a short timescale. In addition, the rapid schedule for Carbonitie-1 was possible due to the investments made by SSTL to investigate ways in order to improve its mass manufacturing capability to make it more streamlined.

Platform and Imager Capabilities

To achieve the challenging schedule and price targets, the satellite design is based on six key principles:

- Image quality to be "good enough" for the intended application
- Single string (except for the receivers that are hot redundant)
- Extensive use of COTS components, including in the imager
- Simple, non-optimized structure
- Use of existing technical solutions whenever possible
- Integration of batch built avionics where possible.

Figure 5: Carbonite-1 during AIT

The project organization was based around a very small core team of five engineers, substantially increasing decision speed. The team was given full autonomy to decide and implement the best solutions, within the wide boundaries set by the business.

The platform is similar in size to the heritage SSTL-100 platform. The main difference is the structure is built around the telescope using central shear walls made of milled aluminium. The avionics equipment was mounted to the shear walls around the imager. The closure and solar panels were made of sandwiched honeycomb panels.

The camera is based on a CMOS detector and provides colour imagery with a GSD of 1.5m at an altitude of 650 km. The satellite can generate still images or videos of the area of interest. By flying the satellite at a lower altitude the GSD can be improved to 1m.

Platform Designed for MegaConstellations

SSTL has been involved with a number of constellations in various capacities, including DMC, RapidEye, KANOPUS, FORMOSAT-7 at spacecraft level, and at payload / subsystem level in ORBCOMM-SG, CYGNUS and the 22 Galileo FOC payloads. The production philosophy typically adopted for such batches of satellites to consider the closest existing product, modify this to the specific mission needs, build a proto flight unit, and then carry out a limited batch production run. As a result, the cost savings that can be achieved in batch production are often limited, as the base design was never optimised for such a batch production.

Using this experience, SSTL initiated an internal Research and Development (R&D) programme in 2011 with the main objective to improve performance to cost ratios even further in order to provide low-cost and reliable spacecraft for individual or constellation missions. By exploiting new commercially developed technologies, protocols and processes, the R&D programme was to offer the equivalent performance of current SSTL small satellite platforms at a significantly improved mass, schedule and price point. This internal development programme heavily leveraged the investments made in other industries in batch manufacturing of highly reliable products.

The process makes significant use of modern automated manufacture and test techniques, and the avionics are designed taking this into consideration. The consequence of this is that significant savings in production costs and schedule are achieved.

By levering the recent advances in production capabilities at SSTL, automated testing and new technologies, provides the biggest jump upwards in performance and the biggest step downwards in platform cost since the SSTL-100 platform was first introduced in the early 2000s.

Platform Design Principles and Drivers

In addition to the five top level design principles identified in §II.1, the Carbonite Series design is developed with some lower level key drivers and principles in mind. These are a combination of (a) principles that SSTL have employed successfully in delivering small satellites in the last 30 years, and (b) new approaches that are enabled by SSTLs' evolution as a company in the last 10 years, specifically the recently developed in-house capabilities for batch/mass production and automated test. The key principles taken forward can be summarised as follows:

- The use of mature, well developed protocols such as Controller Area Network (CAN)
- On board autonomy, resulting in the elimination of the need for expensive, constantly manned ground segments
- Robustness and redundancy (for critical functionality) with simple and robust operational modes
- The use of COTs components and technologies – building on 30 years of successful implementation on operational missions.

- Modularity; investing in the development of only a few key new systems that can be arranged in configurations to deliver a wide variety of performance and capacity variations depending on mission requirements
- Low recurrent costs at 'unit' level; maximising the use of automated manufacture and test capabilities to reduce expensive manpower costs, thereby achieving an extremely low unit level cost

To ensure maximum flexibility and applicability of the Carbonite Series, the following key driver was also identified:

- Compatibility with low-cost auxiliary payload launch opportunities; defining qualification envelopes for the development elements, as well as ensuring that all Carbonite Series platforms are launched powered-off as a baseline.

Platform Designed for Production

Though Carbonite-1 used a majority of heritage SSTL avionics units, the series is designed for core platform elements with maximum production efficiency as a driver. Hence the design takes advantage of automated batch manufacture and test processes. This entails management of a controlled preferred parts list, use of pick and place machines, reflow soldering process, press fit connectors and comprehensive test coverage via automatic test equipment and built-in self-test.

The low cost, batch build philosophy allows for a module level rather than component level stores inventory, drastically reducing the period from customer order to spacecraft delivery. This coupled with the low cost of the recurrent parts, results in extremely low recurrent costs for the core Carbonite series elements.

In recent years SSTL have invested heavily in mass production facilities and processes. These in-house capabilities are now installed and qualified, and are being leveraged to drastically reduce the production costs of the next generation platform elements. The key capabilities are:

- Pick & place of components
- Automated soldering (re-flow)
- Automatic inspection, including X-ray inspection of re-flowed electronics
- Automated test

These factors result in a step change in production approach. Typically when producing space hardware, significant costs are expended both on the raw materials and parts ('Space Qualified' parts being extremely expensive with associated long lead times), and the skilled labour associated with largely manual assembly and test activities. Even if lower cost (e.g. COTs) parts are used, the significant labour elements results in a high cost investment in any space equipment produced in this way. A secondary effect is that the resulting hardware is typically extensively analysed, tested and repaired if it develops a fault – due to the high value, discarding the equipment at the point where the fault is discovered is not a realistic option.

This pattern is broken by the production approach for the Carbonite Series; low cost parts are procured, automated processes are used extensively to manufacture, inspect and test the hardware. Therefore if a fault is detected, during test, for example, the option to simply discard the element in question becomes an easier and more attractive option in the cases where faults can be shown not to be systematic and/or design related.

The automated test theme is carried in to the platform and spacecraft Assembly, Integration, and Test (AIT) phases also, with a platform level Automated Test Equipment (ATE) setup employed to run representative ('test as you fly') scripts and scenarios on the platform. This also contributes to the reduction the costs and durations associated with the AIT phase of the Carbonite Series implementations.

Figure 6: Automated production line

CARBONITE-2 MISSION

Carbonite-1 is still operational after two years, and is sharing its groundstation passes with other commercial satellites operated by SSTL. The satellite is still being used to test out new improved AOCS and imaging techniques and to build heritage on the payload equipment.

At the end of the mission, the de-orbit sail on the platform will be deployed in-order to reduce the altitude and orbital lifetime to within 25 years. Sample videos by from Carbonite-1 have been published [3]

Carbonite-2 is the follow-on demonstrator mission, and is due for launch in 2017. Several improvements have been introduced since basic video imaging capability was confirmed on Carbonite-1.

- Improved geolocation by the addition of a star camera
- Improved telescope and imager design
- Improved data capacity by a factor of x16 with two deployable solar arrays and greater memory capacity and data downlink
- Includes experimentation with additive design technologies, evolutionary design techniques and 3D printing

The basic specifications for the Carbonite-2 spacecraft are provided in table 3. The spacecraft configuration illustrates that the imager is the dominant element, with avionics fitted around the imager.

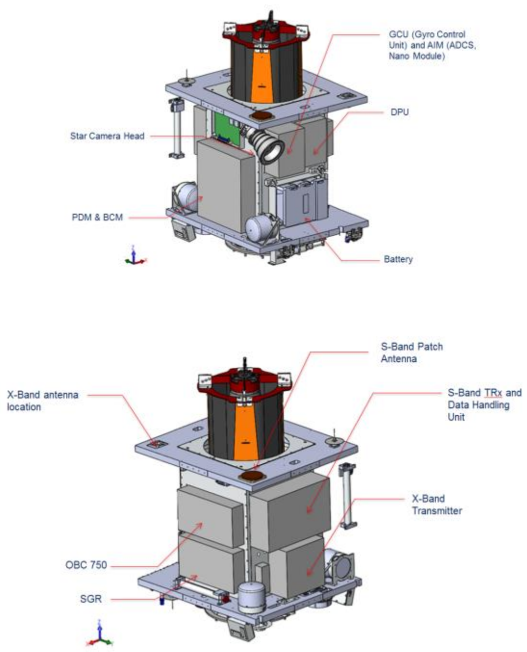

Figure 7: Carbonite-2 configuration

Table 3: Carbonite-2 Specifications

Parameter	Specification
Design lifetime	5 years
Imager	1.2m GSD @550km 5.9x5.9km RGB colour
Imaging modes	Target tracking Strip mapping
Video	Up to 25 fps
Agility	±45 degrees from nadir
Capacity	>1000 image frames per day (typical)

After Carbonite-2, the spacecraft will be production engineered for full batch production in order to optimise constellation cost.

Figure 8: Carbonite-2 during AIT

With the enhanced AOCS, several imaging modes are supported in snapshot and video mode. These include Stripmap, Stereo pair, and mosaic imaging. In video mode target tracking mode is also supported.

In strip mapping mode, video imaging results in a number of overlapping scenes providing opportunities to address applications for low light or high quality imaging through image processing of the combined overlapping scenes.

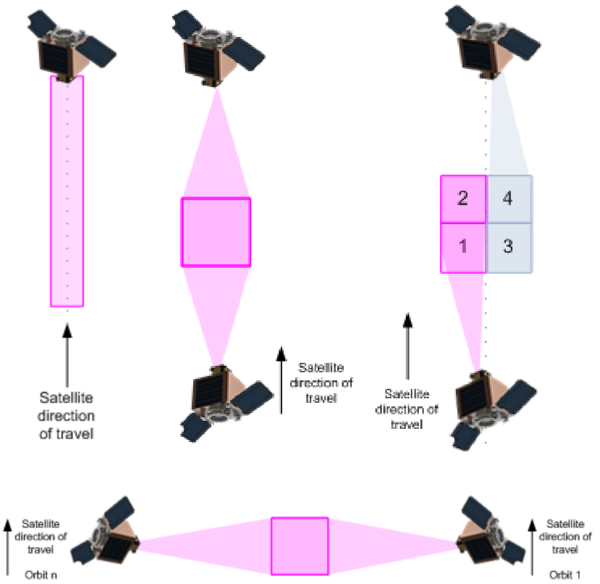

Figure 9: Carbonite-2 imaging modes

FIRST RESULTS

Carbonite-2 was launched on the 12th of January 2018. As part of the commissioning campaign, the spacecraft was contacted from the SSTL groundstation in Surrey on the first pass to start platform checkout and detumble the spacecraft and bring it under 3-axis control.

The instrument includes a focusing mechanism, and payload commissioning in video imaging mode whilst moving the focusing mechanism allows very rapid instrument focusing to be achieved.

The spacecraft will now be used to demonstrate real operational scenarios with data being shared with key mission partners [14], Over 450 videos were captured in the first 100 days of operations, with data being shared with key mission partners [11,12].

Figure 10: Carbonite-2 first results [11, 13]

FUTURE PLANS

The Carbonite series of spacecraft are a series of demonstrators of new Earth Observation applications in preparation for commercial service missions. For some of these missions potential service providers and end-users work in partnership with SSTL.

Future iterations of the Carbonite-1 and -2 video imaging spacecraft are planned to be optimised for batch production to reduce mass and volume further, for implementation of a cost-effective constellation. Furthemore, the video imaging capability is also planned to be included as a separate capability onto the SSTL-300S1 and SSTL-1000S50 high resolution imaging spacecraft.

Figure 2: Carbonite production spacecraft

Carbonite-3 is planned to further refinement of the video imaging platform, whereas Carbonite-4 is planned to focus on other Earth Observation sensors.

CONCLUSION

With the emergence of concepts for super-constellations, the highly bespoke design and production of satellites that has dominated the satellite industry needs to be supplemented. Specialized manufacturing processes that require hand procedures slow down production and keep costs high which make constellation scale manufacturing uneconomical.

SSTL's design and manufacturing philosophy, honed over 30 years, has allowed the development and deployment of a high resolution constellation at a very low cost. In addition, new processes utilizing automated manufacturing and testing processes have been demonstrated on Carbonite-1. The Carbonite series of spacecraft provide high utility by reducing the cost of entry for new and existing business models which includes the deployment of super-constellations. The addition of video capability from a large constellation can lead to new use cases which include persistent monitoring of regional hot spots for change detection. By reducing the cost and schedule per satellite, the Carbonite series can enable these super-constellations thereby providing a unique ability for sub-daily accesses. It will also enable new opportunities and bolter the capabilities of DMC3 type missions by providing higher revisit at a lower cost. This has the potential of disrupting the market by opening up new service areas with new applications that require a high revisit frequency, supplemented with high fidelity imagery, by providing data at a lower cost.

References

List and number all bibliographical references at the end of the paper. When referring to references in the text, type the corresponding reference number in superscript form as shown at the end of this sentence.1 Use the **References** style for formatting citations, as shown in the following examples:

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