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MISC™ – A Novel Approach to Low-Cost Imaging Satellites

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ABSTRACT

By severely limiting satellite size and weight, the popular CubeSat nanosatellite standard realizes noticeable cost savings over traditional satellites in the areas of design, manufacture, launch and operations. To date, there has been limited commercial utilization of CubeSat systems due to the widespread perception in industry that a 10 cm x 10 cm x 30 cm form factor is too constrained for payloads in support of useful missions. In this paper, we argue against this perception by presenting MISC™, a 3U CubeSat capable of providing 7.5 m GSD multispectral imagery from a circular orbit of 540 km. Over an anticipated operational lifetime of 18 months, each MISC will be able to image over 75 million km^2, equivalent to approximately half the Earth's landmass. MISC's novel design combines a robust miniature imager module payload with an existing CubeSat Kit-based bus and a distributed ground station architecture. With anticipated order-of-magnitude cost savings when compared to current commercial offerings, MISC's lifetime system cost should represent an extremely attractive proposition to consumers of satellite imagery that wish to own and operate their own assets. MISC satellites will be available for commercial purchase in mid-2009.

INTRODUCTION

This paper introduces Pumpkin's Miniature Imaging Spacecraft (MISC), a 3U CubeSat capable of providing commercial grade satellite imagery at a CubeSat-sized price.

Building on Pumpkin's space-proven CubeSat Kit family of nanosatellite components, MISC combines cost-saving commercial-off-the-shelf (COTS) nanosatellite components with a custom imager payload and some other mission-specific parts.

The extreme mass and volume limitations available under the CubeSat standard result in a tightly constrained design space. The first half of this paper describes this problem and proposes the components and configuration that we have found to be optimal.

In the second half we discuss the operational environment for MISC, provide parameters of a sample mission, and present arguments for an owner / operator business model.

THE CUBESAT STANDARD

The CubeSat project was originally developed by Stanford University's Space Systems Development Laboratory (SSDL) in conjunction with California Polytechnic State University, in order to provide standardized, low-cost access to space for nanosatellites.[1] This standard sets limits on mass and volume, but provides for a common secondary launch solution through the P-POD deployment system.

Since 2003, over 30 nanosatellites have been launched under this standard. A number of companies have developed COTS components for CubeSat subsystems such as power, communications, onboard processing, and attitude control. The number of non-experimental missions under the CubeSat standard has historically been limited due to the tight packaging requirements and scarcity of on-board power. However, substantial commercial interest has developed over the past year as both the National Science Foundation and the National Reconnaissance Office have announced plans to fund missions and component development.[2, 3]

IMAGING SYSTEM

Photos from Space

NASA Astronauts on the Space Shuttle and International Space Station routinely image the earth using commercially available cameras and lenses.[4] Equipment typically consists of a 35 mm DSLR with a telephoto lens. Unfortunately this combination often exceeds the allowable dimensions of a CubeSat, as shown in Table 1, especially when one considers that the imaging system is the CubeSat's payload, which cannot exceed 20-40 % of available mass and volume.

Table 1: Comparison of imaging systems

Imaging System & Example NASA Image Number	Length (mm)	Volume (cc)	Mass (g)
Kodak DCS760 (with 6 MP Kodak KAF-6303CE CCD) + AF-Nikkor 400 mm f/2.8 (ISS017-E-006975.DCR)	440	10,000	6,300
Nikon D2Xs (with 12.2 MP Nikon CMOS sensor) + AF-Nikkor 180 mm f/2.8 (ISS016-E-27587.JPG)	232	2,700	1,960
Standard 3U CubeSat	340.5	3,500	3,000

We sought to create an imaging system of equivalent or better performance while staying within the confines of a 3U CubeSat's payload. To minimize costs and reduce development time, we chose to use existing 35mm lenses and image sensors. During launch, MISC is likely to encounter a vibrational environment outside the permissible range for standard commercial parts; certainly beyond that experienced by similar systems previously launched aboard the space shuttle.[5] Therefore its components were designed or chosen to minimize the number of – or even eliminate – delicate mechanical parts subject to shock (e.g., lens elements, lens aperture diaphragms, SLR mirrors, etc.).

Maximum Dimensions of CubeSat Payloads

The CubeSat design specification prescribes a spacecraft shape of 100 mm x 100 mm cross-section, and of up to 340.5 mm in overall length for the so-called 3U configuration.[6] The specification also allows the placement of external components of up to 6.5 mm height normal to each face of the CubeSat, as shown in Figure 1. Hence optical elements with a diameter of up to 113 mm are permitted, sighting down the long axis of the CubeSat.

The Rayleigh criterion gives the resolving power *Res* of a lens as

$$\mathrm{Re}s = \frac{1.22 \times \lambda}{d} \qquad (1)$$

where λ = the wavelength of interest and d = the major diameter of the lens. For λ = 510 nm and d = 113 mm, the resultant 5.5 µm is the resolution limit for CubeSats for the visible spectrum. This narrows our choice of image sensor.

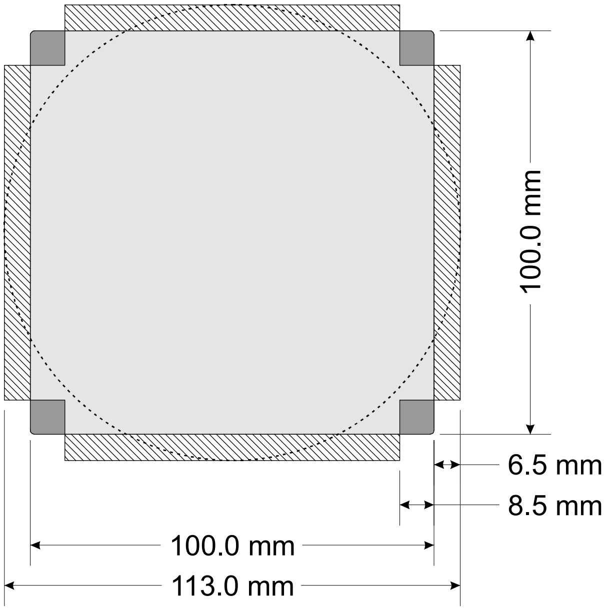

Figure 1: CubeSat Cross-sectional Maximum Dimensions

The 113 mm diameter also prevents the use of "fast" lenses in longer (i.e., over 180 mm) focal lengths, as it is exceeded by the diameter of common fast telephoto lenses; e.g., 200 mm f/2, 300 mm f/2.8, 400 mm f/2.8, etc.[7] This suggests that Ground Sample Distance (GSD) may be diffraction-limited when lenses of longer focal lengths are fitted onto MISC.

Finally, given that the lens and image sensor comprise just one part of an entire 3U CubeSat, we chose to limit the length of the lens to no more than 100 mm, roughly a third of MISC's total length.

Image Sensor

To effectively use 35 mm lenses requires a 36 mm x 24 mm "full-frame" sensor. Some smaller sensors (e.g., APS-C and DX sizes) now have pixels smaller than a CubeSat's theoretical resolution limit. There is also a concomitant loss of field of view when using smaller sensors. We chose the full-frame 16 MP Kodak KAI-16000-CXA-JD interline transfer progressive scan CCD, with a color Bayer RGB filter and a 4872 x 3248 array of 7.4 µm square pixels with microlenses. As an interline transfer CCD, its high-speed electronic shutter eliminates the need for a mechanical shutter, thus improving reliability. The KAI-16000 is readily integrated into available CCD astrophotography cameras. While the KAI-16000 is optimized for color or monochrome imaging in the visible spectrum, by supporting this relatively large sensor we leave open the possibility of selecting other sensors (e.g. ones optimized for other spectra) for alternate future MISC configurations.

Diffraction Perception vs. Pixel Size and Lens Speed

For "pixel peeping" (i.e. viewing a digital image at 100 %), the diameter of the maximum Circle of Confusion (CoC) for a color KAI-16000's 7.4 µm square pixels is 14.8 µm. If two Airy disks become any closer than half their width they are also no longer resolvable (Rayleigh criterion).[8] At f/8, the diameter of the Airy disk is below the CoC at 10.7 µm, yet at f/11 it's just reached it at 14.8 µm. Therefore we limit our search to 35 mm lenses that are f/11 or faster. Amongst 35 mm lenses available today, this limit affects only the telephoto lenses. Shorter lenses are rarely slower than f/5.6 anyway, and they usually achieve their optimum sharpness 2-3 stops closed down from fully open.

Lens Shade

In photography, a lens shade is used to maximize image contrast and quality by eliminating internal reflections from light sources outside the field of view. This becomes particularly important when the Sun is located outside but near the Field of View (FOV). Since the multi-centimeter length of a fixed lens shade for telephoto lenses is a luxury a 3U CubeSat cannot afford, we developed a compact low-mass 4-panel deployable lens shade for use on MISC.

Lens Choices

With a maximum lens diameter of 113 mm, a minimum lens speed of f/11, and a maximum physical length of 100 mm established for MISC, we surveyed a wide range of commonly available lenses for suitability. The "universal donor" Nikon F-mount bayonet with its 46.5 mm register was selected for maximum lens compatibility with the image sensor. Nikon has made over 40 million F-mount lenses, and has supplied 35 mm cameras and lenses to NASA since Apollo 15.[9, 10]

A variety of fixed-focal-length lenses of various constructions and known for their optical performance were chosen as possible candidates for MISC's lens. Most were designed for 35 mm cameras, but some enlarging lenses and medium-format lenses were also considered. All-metal construction was preferred for strength and due to concerns over plastic outgassing. Lenses with electronically-controlled irises, autofocus mechanisms and image stabilization systems were not considered due to concerns over robustness and interface complexity. The survey lenses that are dimensionally compatible with MISC are listed in Table 2.

Table 2: Examples of Lenses Suitable for MISC (Visible Spectrum)

Focal Length (mm)	f/	IC* (mm)	FOV* (°)	Dimensions** (l x d, mm)
5.6	5.6	14.5	185	80 x 70
16	3.5	44	170	51 x 68
15	3.5	44	110	84 x 90
20	3.5	44	94	36 x 64
55	2.8	44	43	62 x 64
60	4	44	40	74 x 65
63	3.5	55	46	34 x 48
80	2.8	85	54	68 x 77
85	2	44	28.5	53 x 63
135	3.5	44	18	82 x 64
500	8	44	5	112 x 88
600	8	44	4	99 x 106

*: Some Image Circle and Field of View values are approximate or inferred. Field of View values are native to the intended format and are *not* normalized to the 35 mm format's nominal Image Circle of 44 mm.

**: The listed lengths for enlarging and medium-format lenses are compatible with the Nikon F-mount's 46.5 mm register.

Many of these lenses are no longer in production, but are readily available in the secondhand market. Most weigh less than 600 g. The short lengths of the lenses above enable their integration into MISC as part of the optical payload while still leaving room for the remaining spacecraft subsystems. Common telephoto lenses – even slow ones like the 200 mm f/4 – are typically too long for MISC.

We conclude that MISC can easily accommodate a wide range of existing fisheye, wide-angle, normal and moderate telephoto 35 mm lenses for various imaging applications in the visible band. Most of these lenses also have good IR performance. At least one (the CoastalOpt® UV-VIS-IR 60mm f/4) has a usable transmission in the UV range as well.[11]

Where best possible GSD is the driving factor, only one class of 35 mm lenses – f/8 catadioptric lenses of 500-600 mm focal length – are sufficiently small to fit in MISC and have the required narrow FOVs. Faster (e.g., f/5) catadioptric lenses in these focal lengths are rare and have considerably larger diameters that exceed the CubeSat's physical envelope.

Impact of GSD Potential on Lens Choice

A 600 mm f/8 lens has a maximum aperture of 75 mm. The Rayleigh limit for this lens at λ = 510 nm is 8.3 µm. The relationship between the sensor pixel size *p*, the lens focal length *FL*, the ground resolution *R* and the satellite altitude *A* is given by

$$\frac{R}{p}=\frac{A}{FL} \tag{2}$$

Assuming a 600 km LEO orbit and a 600 mm lens, the ratio of the ground resolution to pixel size is 1 million to 1. This yields a ground resolution of 7.4 m, given the 7.4 µm square pixels of the KAI-16000. At this altitude the KAI-16000 pixel size is smaller than the Rayleigh limit. To make best use of MISC's diffraction-limited lens and imager combination, we reduce MISC's altitude to 540km, effectively enlarging what each sensor pixel "sees."

$$R=\frac{p\times A}{FL} \tag{3a}$$

$$R=\frac{8.3\mu m\times 540km}{600mm} \tag{3b}$$

$$R=7.5m \tag{3c}$$

At this altitude, each sensor pixel maps to a 6.7 m square on the ground. But diffraction limits the GSD to 7.5 m, as each barely-resolvable 8.3 µm square on the sensor maps to a 7.5 m ground square. Thus, at 540 km, MISC's ground patch measures 32.5 km x 21.6 km, for 702 km^2 per 16 MP image captured.

Therefore for applications seeking the best possible GSD, a 600 mm f/8 lens is both eminently suitable and the minimum requirement for MISC at the commonly used LEO altitude of 540 km. Since froman imaging perspective the use of lenses of shorter focal lengths is much "easier" in terms of depth of field, maximum exposure time, etc. the remainder of this paper is focused on the ground-imaging version of MISC, using a 600 mm f/8 lens to deliver a GSD of 7.5m.

Zone of Acceptable Sharpness

For a 600 mm f/8 lens and a subject located at a distance of 540 km, the hyperfocal distance of 3000 m yields everything from 1500 m to infinity in acceptable sharpness, assuming a CoC of 15 µm. This suggests that a fixed focus can be employed, thus greatly simplifying construction and maximizing robustness. It also suggests that MISC is capable of sharply imaging anything it is oriented towards, as long as the target is 1.5 km or more away and is sufficiently illuminated.

Exposure for Image Capture

For a 7,500 m/s satellite ground speed and a 7.5 m GSD, exposure times should be kept shorter than 1/2000 s to avoid motion blur. The "Sunny 16" rule for outdoor subjects in bright sunlight corresponds to an Exposure Value (EV) of 15.[12, 13] Exposures for scenes darker or brighter than EV15 can be achieved by increasing the imager's equivalent sensitivity or reducing the exposure time, respectively. Sensor noise limits low EV performance, and the KAI-16000's minimum exposure time limits high EV exposures. Camera settings for various exposure values are shown in Table 4.

Table 3: Camera Settings for Common Conditions

Subject Lighting Condition	EV	ISO	Exposure Time (µs)	Aperture
overcast	12	3,200	500	f/8
cloudy-bright	13	1,600		
weak, hazy sun	14	800		
bright sun	15	400		
bright daylight on sand or snow	16	200	500	
		400	250	
extremely bright	17	100	500	
		200	250	
		400	125	
	18	100	250	
		200	125	
		400	67	
	19	100	125	
		200	67	

For alternate, non-terrestrial targets moving slowly across MISC's FOV, exposure times considerably longer than 500 µs can be used, as the DSLR components (mechanical shutter, mirror return assembly, etc.) whose vibrations typically compromise telephoto image capture are absent from MISC.

Modern DSLRs have database-driven sophisticated color meters for automatic exposure control.[14] For optimum image quality MISC's on-board camera computer will employ different techniques – including "area of interest" monitoring in lieu of preset exposure settings – to deliver accurate exposures over terrain with changing and/or unpredictable brightness.

Specifications

The characteristics and performance of MISC's imager payload are shown in Table 4, for an altitude of 540 km.

Table 4: Imaging Payload 600-75-16-VIS Overview

Characteristic	Value
Focal Length	600 mm
Aperture	75 mm (f/8)
Rayleigh limit (λ = 510 nm)	8.3 µm
Hyperfocal Distance (CoC = 15 µm)	3000 m
Image Size	16 MP
Response	380 nm - 700 nm
Imager Dimensions	36.1 mm x 24.0 mm
Active Pixels	4872 x 3248
Pixel Size	7.4 µm x 7.4 µm
Ground Square per Sensor Pixel	6.7 m
Ground Patch	32.5 km x 21.6 km
Ground Area per Image	702 km^2
GSD (diffraction-limited)	7.5 m
Maximum Exposure Time	500 µs
Capture Speed	16 MP/s

Imager Payload

After a comprehensive lens survey, a quantity of identical 600 mm f/8 catadioptric lenses from a reputable manufacturer was acquired through retail channels. These lenses for 35 mm cameras exhibit excellent correction of axial and off-axis aberrations. Their solid construction enables them to withstand the rigors of a shake table, simulating launch. Their focus sensitivity to temperature is also very low.

Based on the maximum dimensions of this 600 mm f/8 lens design and with MISC's requirement to accept nearly all F-mount lenses of moderate length, a complex imager payload was developed. It is illustrated in Figure 2. It consists of multiple custom CNC'd aluminum parts designed to assemble this lens (and alternately, many smaller lenses) together with the KAI-16000 sensor and its custom drive / interface circuitry. The overriding design objectives of mechanical robustness, preserving compatibility with the mechanical requirements of the CubeSat specification and maintaining accurate registration of the sensor plane were all met. The costs associated with exotic materials do not currently show sufficient benefit. The volumes dedicated to electronics have considerable capability for future expansion. An oversize image circle of 57 mm is supported. In this form the imager payload forms the top third of MISC, and also provides the attachment point for panel hinges.

The camera portion of the imager payload is derived from a COTS astrophotography camera. Working with its manufacturer, we discarded the enclosure (approximately 1U in size itself), heatsink, cooling system and shutter. The existing sensor interface was preserved, and the remaining electronics were redesigned to be compatible with the physical envelope of the imager payload, the on-board connectors and MISC's +5 V power bus. Since MISC's typical output is terrestrial imagery, we considered the deletion of the camera's voluminous CCD cooling system to be acceptable. The sensor is thermally coupled through the imager payload's base plate to the large ADACS mass below it.

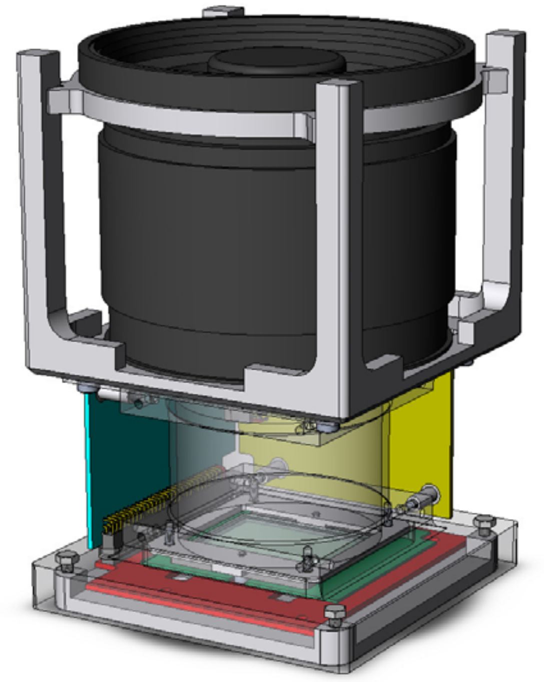

Figure 2: MISC Imager Payload 600-75-16-VIS.

Optical filters for exposure adjustment or particular spectra can be fitted at time of manufacture within the imager payload.

The relatively slow lens speed of f/8 is deemed sufficient to protect the shutterless imager from damage due to short-term direct exposure to the Sun. The ADACS (see below) can also actively orient MISC away from the Sun.

ATTITUDE DETERMINATION AND CONTROL

With its 1 ° native 3-axis pointing capability, the COTS IMI-100 ADACS delivers acceptable accuracy even in the tight 4 ° FOV case for the 600 mm f/8 lens. The ADACS and its support electronics form the center portion of MISC.

The pointing accuracy of the on-board ADACS enables MISC to use transmit antennas that are substantially more directional than those of a typical CubeSat (with passive attitude stabilization). With the downlink antenna(s) pointing directly at the ground target, a minimum of attitude slewing is required between image capture and image download operations.

The ADACS also enables MISC to put its deployable lens shade to best possible use. For a nadir-pointing attitude at high noon, the lens shade may be all but superfluous. But for other situations, it can be highly desirable.

REMAINING MISC SUBSYSTEMS

The remaining portion of MISC consists of a single-board computer (SBC), an EPS, a VHF/UHF transceiver, a C&DH module, solar panels and antennas. These are located in the bottom section of MISC.

SBC

A COTS +5 V PC/104 x86-class SBC was chosen for the camera computer. Connected via USB 2.0 to the camera, it uses a software development toolkit (SDK) to perform metering via area-of-interest, exposure settings, image capture, JPEG compression and database management. The SBC communicates with the C&DH module over USB for scheduling, configuration, image transfer, etc. The SBC can also access the VHF/UHF transceiver directly.

EPS

The EPS is a factory-optioned space EPS with dual +5 V output stages and enhanced output current ratings.

VHF/UHF Transceiver

The VHF/UHF transceiver is a new offering in a CubeSat Kit™-compatible footprint with 1W transmit power and a very low receive current.

C&DH

The C&DH is a space-proven micropower unit with up to 2 GB of on-board storage and SSDL flight software. It communicates with the SBC as a USB device.

Solar Panels & Lens Shade

The deployable solar panels are based on existing Clyde Space catalog items, using a Pumpkin solar panel hinge. Roughly 2.5 U in length, the four solar panels are deployed at right angles to MISC's sides. The panels deploy automatically upon MISC's ejection from the P-POD deployer.

The lens shade consists of four lightweight panels that also deploy from the Pumpkin solar panel hinge. They shield the front of MISC's 600 mm lens from stray light.

Antennas

The design of the antennas is not yet finalized, but will draw on the experiences of previous CubeSats with VHF/UHF systems onboard. The ADACS enables us to confine the pattern to be earthward, thereby increasing the gain by 3 dBi.

ASSEMBLING MISC

Table 5 lists the various hardware components that make up MISC, with their masses. MISC is "nose-heavy," with the Imager Payload and ADACS concentrated in the earth-facing two thirds of the satellite. By using several COTS components, we held costs down in keeping with the low-cost CubeSat paradigm.

Table 5: MISC Components & Masses

Component	COTS / Custom	Mfg	Mass* (g)
CubeSat Kit Imager Payload 600-75-16-VIS	Custom**	Pumpkin	1,998
IMI-100 ADACS	COTS	IMI	979
Cool LiteRunner 2 SBC with CF Mass Storage	COTS	Lippert	145
15W EPS + Battery	COTS, w/option	Clyde Space	150
VHF/UHF Transceiver	COTS	AstroDev	78
CubeSat Kit FM430 Flight Module	COTS	Pumpkin	90
Antenna(s)	Custom	SSDL	100
Deployable Solar Panels & Lens Shade	Custom	Clyde Space & Pumpkin	650
CubeSat Kit Structure	COTS	Pumpkin	160
Cabling	Custom	Pumpkin	40
Miscellany	Custom	Pumpkin	100
		Total	4,490

*: Some masses for non-COTS items are estimated and are subject to change.

**: The 600-75-16-VIS Imager Payload is intended to become a standard Pumpkin line item for use in MISC spacecraft.

MISC's mass considerably exceeds the typical specified 3 kg per 3U CubeSat. However, there is launch precedent for 3U CubeSats exceeding 3 kg; QuakeSat-1 – QuakeFinder's 3U CubeSat for ULF earthquake precursor sensing – weighed in at 4.5 kg.[15] The net effect of the excess mass is limited to an increase in launch costs and a non-critical shift in the CubeSat's center of gravity.

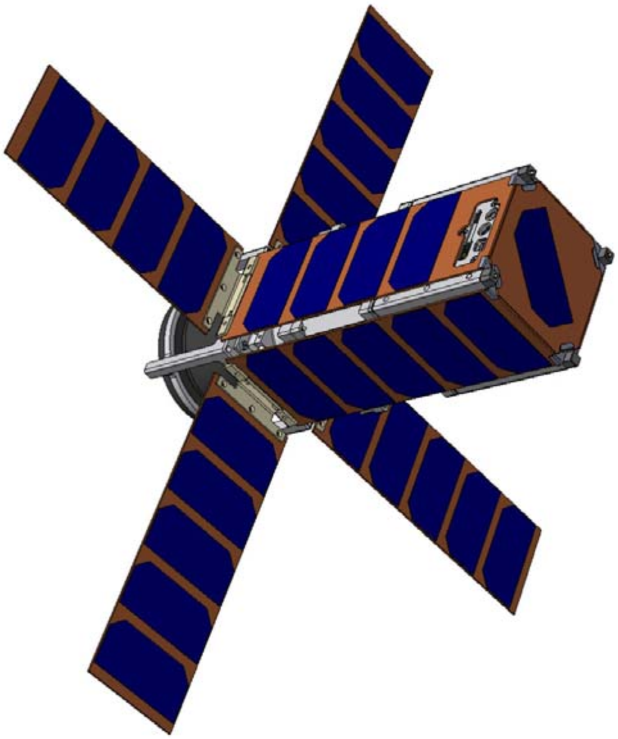

Figure 3: Rear View of MISC Prototype

Operational Lifetime

Like the majority of CubeSats that have been launched to date, MISC is designed for low costs and not for a 10-plus-year lifetime. An operational lifetime of 12-24 months per MISC is expected. The impact of this on the business case for MISC is discussed below.

ALTERNATE CONFIGURATIONS

Other Sensors

The maximum image circle that can be accommodated by the design of the MISC imager payload is 57 mm. As this is considerably larger than that of 35 mm lenses and full-frame sensors (43.3 mm diagonal), lenses with a larger image circle could be paired with larger sensors for greater data capture per image. Alternately, multiple smaller sensors could be accommodated within the 57 mm imaging circle of such a lens.

At a later date we may undertake a design effort to equip MISC with multiple selectable filters for single-sensor multispectral image capture. This will require substantial additional mechanism design, due to the lack of available volume within the image circle cylinder.

Other Lenses

Broad area imaging MISC configurations with lenses of shorter focal lengths have the potential to be lighter than the total mass shown in Table 5 by several hundred grams. In many cases they also free up additional volume around the lens that could be used for other nanosatellite components (e.g., additional batteries, sensors, antennas or miniature payloads).

Other Transceivers

Replacing the VHF/UHF transceiver with an S-band transceiver, or augmenting the existing MISC with an S-band transceiver, will require an additional EPS due to the S-band transceiver's expected high power requirements. This will likely require removing the SBC from the tail end of MISC and replacing it with a smaller SBC in the Imager Payload. A variety of antenna configurations are being considered.

MISC MEANS BUSINESS

Small satellites are big business because satellite cost increases dramatically with design factors such as size, component count and operational lifetime. The primary motivation behind MISC is to limit these quantities so that satellite ownership becomes a reasonable option for individual businesses with a need for substantial quantities of satellite imagery.

Current medium resolution satellite imagery is expensive due to the enormous fixed costs of traditional imaging satellites, as well as the lack of aggressive competition resulting from few providers and previously high barriers to entry. Service is negatively affected by the priority of a given customer as well as by government discretion in the case of joint-venture satellites. For customers with infrequent imagery needs, the existing model will likely continue to remain the best option.

However, many commercial, non-profit, and local government entities would benefit greatly by owning and operating their own imaging satellite assets. For instance, growing communities such as environmental monitoring and risk management can significantly enhance their effectiveness with direct access to earth imaging resources. These owner / operators would have full control over the targeting portfolio of the imaging satellite as well as nearly instant – and exclusive – access to the images. By owning and operating their satellite assets, these organizations can pocket the profits that would normally go to satellite imagery providers. They may even be able to offset their costs by re-selling their images, as they will own the rights to those images. Additionally, as the anticipated lifetime of the MISC system is 1-2 years, these entities will benefit operationally from the use of advancing commercial technology that can be introduced into the satellite system every two years instead of the 5-10 year operations cycle commonly associated with traditional systems.

We believe that these benefits will be attractive to many industries. However, there are up-front capital costs and business risks associated with owning the asset which do not exist when simply purchasing images from a commercial provider. The dramatically lower investment cost of MISC – as well as the ability to orbit multiple (concurrent or subsequent) MISCs instead of a single traditional satellite – mitigate this risk.

Although MISC pricing is not finalized, we anticipate that MISC will be a very attractive option for entities requiring large quantities of satellite imagery in support of their operations.

Launch Options and Costs

CubeSats launch as secondary payloads and offer extremely attractive launch prices compared to even low-cost dedicated launch systems. At approximately $150,000 to $300,000 per launch, the 3U CubeSat standard offers at least an order of magnitude cost savings over alternative imaging satellites. Moreover, replacement at the end of MISC's 18 month projected lifespan does not pose a substantial impediment to its commercial attractiveness.

The EELV Secondary Payload Adapter (ESPA) – developed by CSA engineering under Air Force SBIR – offers tremendous potential to lower the cost of launch for satellites on the order of 100 kg.[16] However, this secondary launch market has not yet stabilized to a point where launch and integration costs may be reliably ascertained for repeated launches.

The most cost effective dedicated launch option – aboard the SpaceX Falcon 1 – is currently advertised at $7.9 million per launch.[17] Taking into account a best-case estimated launch cost of $5-6 million for a single ESPA port and the risk associated with the unproven Falcon 1, it is clear that a MISC launch aboard a proven launch vehicle would offer an extremely attractive launch option for customers considering extension to satellite operations.

ON-ORBIT OPERATIONS

MISC on-orbit operations are comprised of two main modes: image targeting / ground control and image downlink. Due to power constraints these two modes are currently exclusive.

Image Targeting and Ground Control

During imaging, the satellite slews towards the target, powers up the camera, captures a number of images and downloads them to a storage unit. Target identification and prioritization will require little specialized knowledge or training. A ground controller will interface to the satellite's scheduling queue through a graphical user interface and will essentially consist of highlighting areas on a global map. Each target will be assigned a priority and on-board processing will determine exactly how to decompose the requested assignments into individual images.

Image Downlink

Downlink represents a major design trade in the system. The current MISC design calls for downlink capability at either 38.4 kbps or 57.6 kbps using an AstroDev Helium-100 UHF/VHF radio. Exact frequencies have yet to be specified pending FCC and similar foreign entity licensing requirements. The primary benefit of using UHF/VHF bands for spacecraft communications – beyond the current availability of a commercial CubeSat UHF/VHF radio – is that supporting ground stations can be deployed worldwide cost effectively and with relative ease. On the other hand, the relatively low data rates realizable on the UHF/VHF bands require a large ground station network to downlink the 196 images captured per day.

We are actively seeking an upgrade path to an S-Band transceiver with transmission speeds approaching 1 Mbps. This capability would enable us to support the current baseline daily operations with significantly fewer ground stations, on the order of 2-3 stations total. Alternately, with ground station coverage equal to that of the UHF/VHF system, this added data transmission capacity could enable substantially larger daily imaging areas, though specific performance analysis is limited until a viable S-Band radio manifests itself commercially. Lastly, S-Band communications would allow directional antennas and beam shaping techniques to be employed, better leveraging MISC's ADACS capability while using MISC's power system more effectively.

Bus Operations

Individual owner/operators will have full control over targeting and downlink with support on satellite software upgrades and operational troubleshooting provided by Pumpkin and its affiliates under a service contract. This allows owner/operators to gain the benefits of an individualized imaging system without the need for expensive in-house technical resources for maintaining satellite operations.

End-of-Life and Deorbit

In 540 km LEO orbits MISC satisfies current guidelines for passive deorbiting. In contrast to traditional imaging satellites, whose re-entry at end-of-life or upon system failure has sometimes been considered a risk due to their large mass and toxic fuel systems, MISC poses no such risk.[18]

Operational Example

Since the actual benefit of the MISC approach is only apparent through a comprehensive analysis of lifetime operations, we present an operational example below.

For reference, this example shows a single satellite system capable of providing multispectral 7.5 m GSD imagery for an area equivalent to half the landmass of the entire Earth over the course of 18 months. This would include the entire landmass of the world's 12 largest countries.

Table 6: Example MISC Mission Parameters

Parameter	Value
Altitude	540 km
Orbital Type	Circular
Inclination	45 °
Orbital Period	95.3 min
Fraction Of Orbit Illuminated	.64
Ground Sample Distance	7.5 m
Image Area	702 km^2
Number of Ground Stations	13
Downlink Rate	57.6 kbps
Images Downloaded Per Day	196
Area Imaged Per Day	137,500 km^2
Design Lifetime	1.5 years
Lifetime Area Imaged	75,330,000 km^2

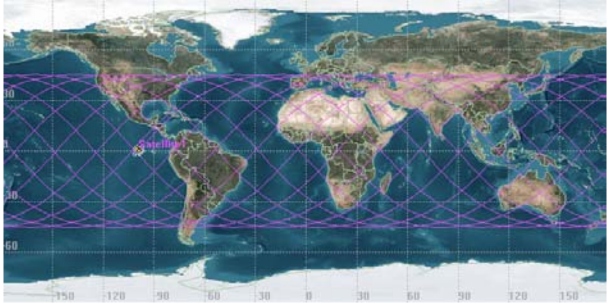

Figure 4: Example MISC Mission Ground Track

In addition to basic orbital theory and Satellite Toolkit (STK), we base this analysis on several assumptions. With approximately 6 minutes of contact time with each ground station per orbit and a design goal of at least one image download per ground station per orbit, we are limited to an image size of approximately 1.7 MB using 38.4 kpbs or 2.6 MB using 57.6 kpbs. We believe this is feasible using acceptable compression techniques.

With a mean orbital period of approximately 95 minutes and 6 minutes contact time per ground station, the amount of available imaging time per orbit is linear as shown below. Assuming an average of 1 minute for each image capture, including targeting and mode switching, suggests that with 13 ground stations MISC could provide 196 images per day for a net imaging area of approximately 137,500 km^2 per day.

Further, we have constructed a basic operational simulation in MATLAB that tracks battery charge through the daily cycle. Results are shown below for the simple case where the satellite takes 13 images shortly after sunrise during each orbit.

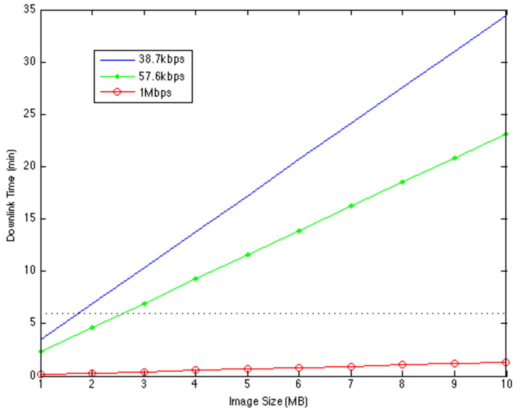

Figure 5: Image Download Times for Various Downlink Rates

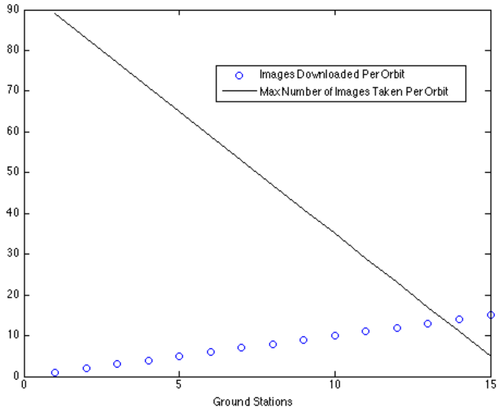

Figure 6: Number of Downloadable Images vs. Imaging Time per Orbit

It then downloads these images continuously throughout the remainder of the orbit. For the numbers shown below, we maintain positive battery charge while remaining within the charge and discharge rates of our power and battery system. Note that we assume the satellite is continuously pointed towards the sun during downlink mode to maximize power generation. Because UHF/VHF directional antennas do not easily fit within a 3U form factor, and link analysis indicates that only a monopole antenna is required on orbit, we believe this to be a reasonable assumption.

Table 7: MISC Power Requirements & Generation

	Power Generated (W)	Power Consumed (W)
Imaging Mode	7.83	13.51
Downlink Mode	19.0	10.01

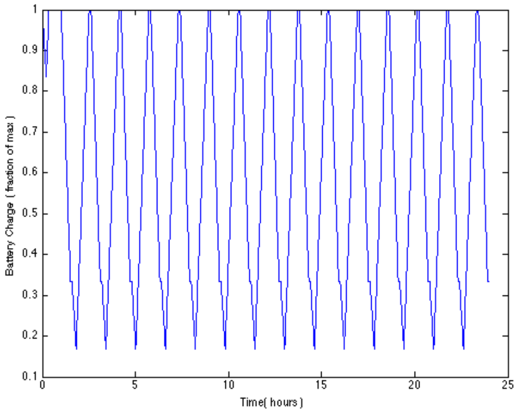

Figure 7: MISC Battery Charge over Orbital Period

AVAILABILITY

MISC is currently in an advanced prototype stage and is expected to enter production by the first half of 2009.

CONCLUSION

By integrating a COTS lens and sensor into a custom imager payload, the MISC earth-imaging satellite delivers 7.5 m GSD for a 540 km LEO orbit in an economical 3U CubeSat package.

MISC is expected to deliver nearly 200 high-quality images per day, with a lifetime area coverage of 75 million km^2. Given MISC's extremely low-cost acquisition, launch and operations costs, we feel that this miniature imaging spacecraft represents a quantum leap in providing affordable satellite imagery.

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TRADEMARK NOTICE

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Note: All web links were retrieved on or prior to June 10, 2008.

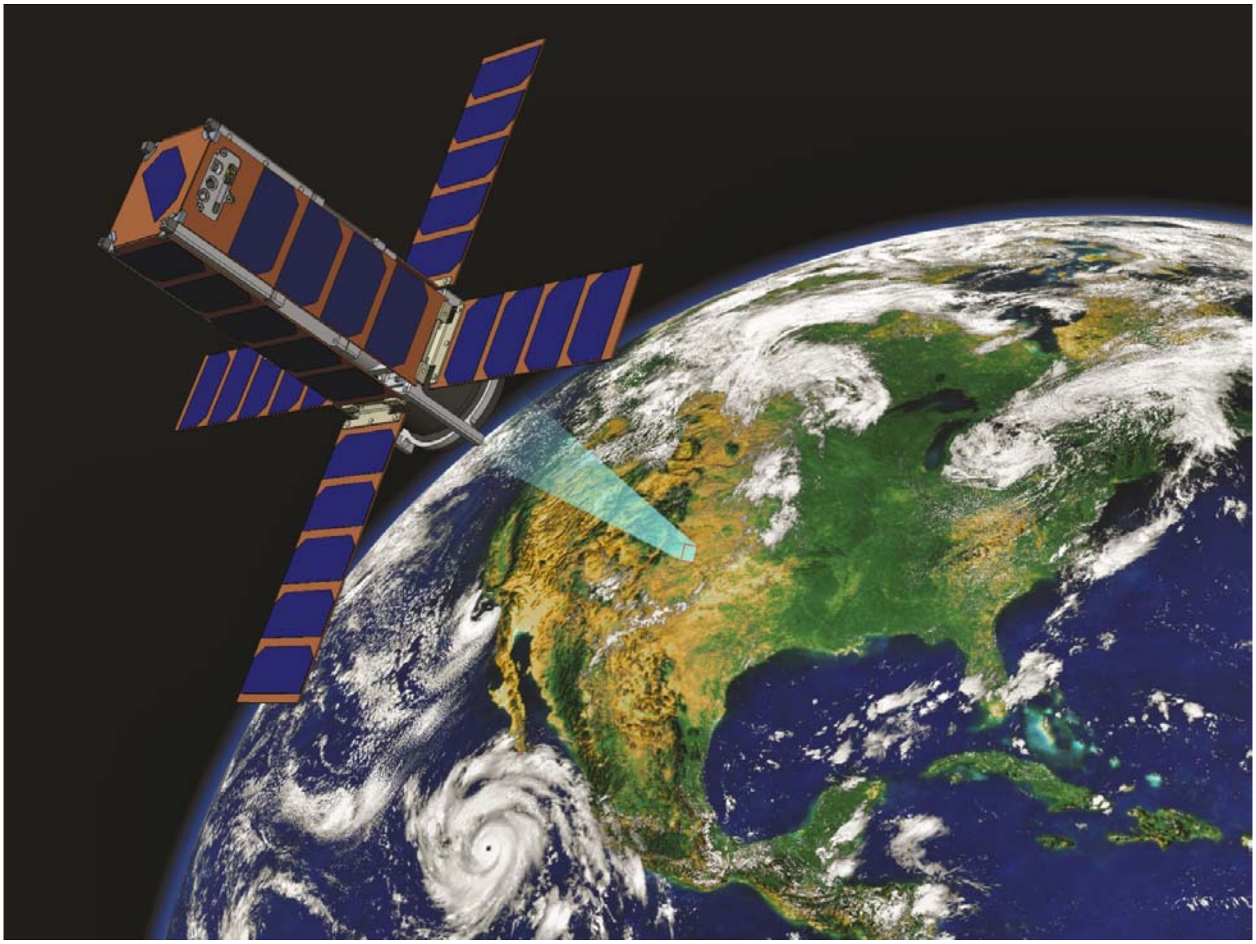

Figure 8: Artist's Rendering of MISC Operating over North America