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# Astronomical Impact of a Low Earth Orbiting Optical Flash Outreach and Education Project

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ABSTRACT

Lightcube is a student-built cubesat with an optical flash bulb which can be radio-activated by anyone and seen with the naked eye. The project goal is to provide members of the public an immediate and powerful connection to space and to the night sky. The massive increase in number of low orbiting spacecraft in the last decade has had a notable impact on astronomical observations and even on the appearance of the night sky. Here we study the potential impact of Lightcube on astronomical observations, potential mitigations, and opportunities for collaboration. Active emitters are rare and none has yet to succeed in producing a naked eye source. Optical interference has been studied primarily in the context of sunlight reflections of diffuse and specular type. The vast majority of new sources are diffuse reflectors, visible when in sunlight. Lightcube's short 1ms flash occurring at a minimum period of 30s makes it most similar to the specular type. The flash pulse peaks at an apparent magnitude of -1, but considering the integration time of the dark adapted eye will depend on the viewer but generally closer to magnitude 6. We consider the impact on state of the art astronomy observations with a short case study. Such events are most likely to appear in sensitive, wide-field, transient observations. A leading project of this type is the Vera Rubin Observatory. The apparent brightness in VRO images is predicted, based on laboratory measurements of the light curve and spectrum and considering the planned length of exposures, to be no brighter than 11th magnitude. Such flashes if detected pose no harm to the instrument or corrupt surrounding pixels. Assuming worst case rates of occurrence, flash events coinciding with observations will likely be filtered by cosmic ray rejection. However, due to the difference in flash morphology, there is a small chance for Lightcube flashes to enter the LSST event stream at a worst case rate of 8 per million. In these cases additional information such as the known orbital parameters of the cubesat can provide further event discrimination.

*Keywords:* Optical Interference, satellites, education

## 1. INTRODUCTION

Rapid gains in electronic miniaturization, mechanical fabrication, and the falling cost of access to space have made it possible for students to build and fly small satellites. This has dramatically opened new opportunities for learning by doing. At the same time, these same advances have also driven an explosion in commercial uses of space. Some of these propose to use large constellations whos reflective properties make them bright astronomical objects. With proposed numbers in the tens of thousands these pose a new confounding factor to science and a visible change in the night sky. At this time little legal framework exists to limit these impacts but cooperation with those advocating for dark skies is proceeding on a voluntary basis. Implementation of government protection in this area will require strong public support making education and outreach more important than ever. Interactive demonstrations which present simple, observable, facts are powerful examples. Lightcube is a student-built cubesat with a remote controlled flashbulb that can be triggered with a low cost radio by anyone which aims to connect more people to space and the night sky.

Orbiting optical light sources are popular educational satellite projects. An early example is the Starshine program where mirrored spheres in low earth orbit were used to measure the upper atmosphere(Maley et al. 2002). The mirror segments were hand-polished by schoolchildren around the country and the public reported naked eye observations which were used to measure the orbital decay due to drag. More recently, active emitters have been used. One early example was FitSat which used a panel of LEDs(Tanaka et al. 2015). However it was only visible with binoculars or long exposure with a camera. Having limited publicity and requiring special equipment, it was observed only by a small number dedicated technically proficient amateurs around the world. Encouraged by FitSat's technical success subsequent missions followed. These included LEDSat (Seitzer et al. 2018) which experimented with using LEDs to identify the satellite and Equisat which had the goal of making a visible flash and being an open-source hardware project with all design elements online[1]. LEDsat had a peak brightness of 8th magnitude requiring amplification to see. Equisat used high intensity LEDs and an experimental battery to reach a magnitude as bright as 3, but did not in the end make a visible flash.

Though the potential for making a broad impact on any global citizen able to see, none of these objects have been widely viewed by the public. One reason for this is that the systems are set up to be used by technically proficient radio operators. Another is that a satellites are technically challenging to build, at least a quarter of student missions fail upon deployment and many more do not achieve full operational status (Swartwout & Jayne 2016; Seitzer et al. 2018).

The goal of the Lightcube mission is to lower the technical barrier to entry for members of the public and provide an interactive connection to space a person can see with their own eyes. The satellite will allow any user with a low cost radio and amateur license to trigger a light which is visible to the naked eye. Direct control of an optically visible satellite by the public has never been attempted before. The spacecraft design is optimized for this use case with a more sensitive radio receiver to enable smaller user radios as well as features which improve visibility within urban areas including stabilized orientation and brighter flash. The design is also optimized to minimize impacts on astronomical observations with a very short flash length, a long hold-off period between pulses, narrowed light projection cone, and the ability to disable from the ground. After discussion with the broader astronomy community, time-stamped logging of flashes will be added if resources permit.

Lightcube is a student project collaboration between students at Arizona State University (ASU), Cetys Universidad Mexicali, and Vega Space Systems a startup founded by recent ASU graduates. Over thirty students have participated in its design and testing. The mission is managed by the ASU Interplanetary Initiative which is directed by one of us (DCJ) who is also a professor of astronomical instrumentation in ASU's School of Earth and Space Exploration. Launch service is provided by NASA Cubesat Launch Initiative which imposes safety and regulatory requirements including an astronomical impact study. Over the course of a three year development process Lightcube has been reviewed three times by engineering experts and members of the astronomy community. These reviews resulted in additional safety features and motivated more testing of prototypes. Launch is expected no earlier than the fourth quarter of 2022. Technical details and news about launch operations will be posted online at lightcube.space.

In the rest of this paper we provide details about the mission setup S2 including optical properties S2.1 and spacecraft operations S2.3. Optical emitter satellites can pose interference to both radio and optical astronomical observations. In S3 we discuss types of optical interference and identify Lightcube as a type of transient similar to satellite specular reflections. In section S4 we estimate the scale of the impact by considering the Vera Rubin Observatory (VRO) - LSST program as a worst case scenario. In S4.1 we estimate the frequency of detection in these two observatories, calculate apparent magnitudes and discuss the impacts on observations.

## 2. SYSTEM DESIGN

The Lightcube cubesat design is optimized to allow commanding from a low power radio transmitter and delivery of an easily visible naked eye signal. An amateur radio transceiver, modified for space flight operates on 437MHz using a deployable quad polar antenna. An audio modem chip accepts uplink commands in Dual Tone Multi-Frequency (DTMF) and can respond either in DTMF or with data encoded using Radio TeleTYpe (RTTY). Commands are uplinked as a series of tones and responses

The light bulb is oriented towards the Earth with a deployable gravity gradient boom made from a mass on the end of a spring wire which is stowed wrapped around the spacecraft body and deployed with a burn wire. This orientation

[1] https://brownspace.org/equisat/

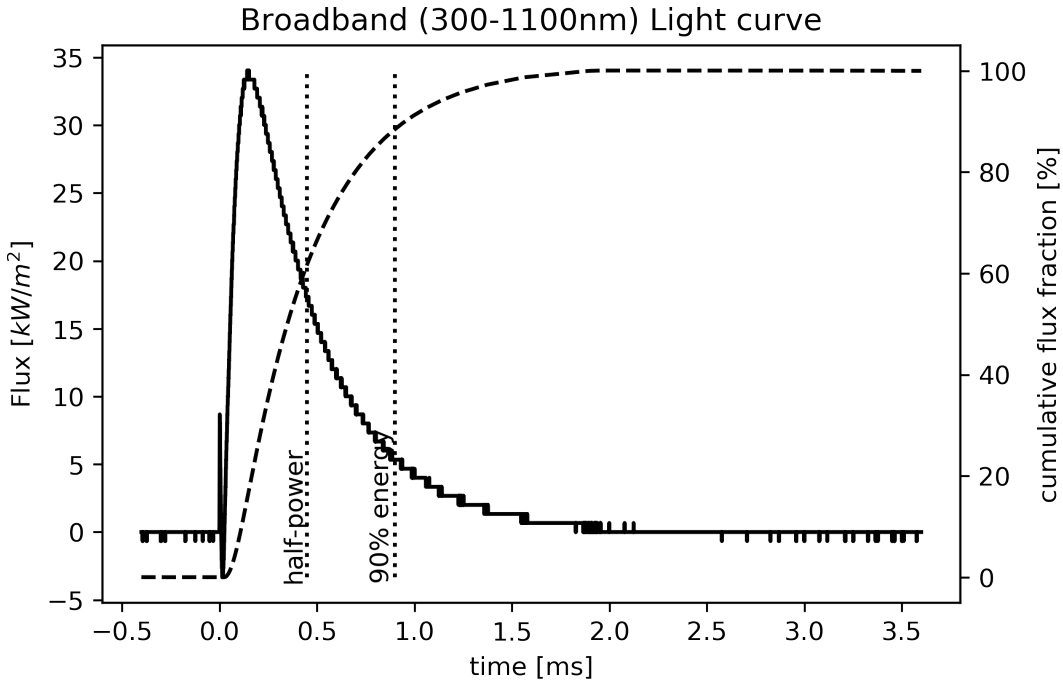


**Figure 1.** Flash light curve measured in the laboratory using an engineering design unit. The Xenon tube generates a flash with full width half max of 0.5 milliseconds.

scheme is completely passive could deploy in either up or down polarity. Flash bulbs are located on both possible orientations and paired with an infrared sensor to select the Earth-facing direction.

### 2.1. *Flash*

The mission goal is to create a flash visible to the naked eye. Most people live in urban centers where only the brightest stars are visible on a clear night. The Lightcube system has been designed to make a visible pulse roughly as bright as Sirius, with an apparent magnitude of -1.5. The realized intensity depends on a number of factors including the performance of the capacitor charging circuit, the configuration of the bulb reflector, and spacecraft attitude.

The flash driver consists of a large capacitor which is charged by a high voltage transformer that delivers current slowly over about 10 seconds. This process is monitored by a central controller, once charge reaches the desired level the charger is switched off and the flash is ready to fire. The charge level is a settable parameter which controls the intensity of the flash. While the capacitor is connected in parallel to the flash tube at all times, the plasma discharge can only occur after a high voltage trigger pulse is applied to the flash tube. Once triggered, the tube, mounted on one face of the cubesat, emits light. A laboratory measurement of the light output curve, shown in Figure 1, exhibits a typical pulse length full width, half max of about .45 milliseconds and a peak intensity of $35\text{kW/m}^2$, measured at a distance of 0.38m.

The charging circuit also includes several safety features. A discharge circuit safely discharges the capacitors if the satellite foot switches register contact with the deployer. Typical terrestrial flashes use electrolytic capacitors to supply the high -of order 1mF- capacitance and high -above 500V- voltages. However, these types of capacitors are subject to vacuum driven trapped gas explosion and cannot be used in space. Metallized Polypropylene Film (MP) capacitors, which have a solid construction that is not subject to this issue, are used instead. These capacitors are a recent technological development, driven by the need for high reliability solar inverters. The charging circuit itself features overvoltage and overcurrent monitoring. If such a condition is detected, capacitor charging will immediately stop, requiring active re-enabling of the charging process via the on-board controller. The capacitors will only be charged when a flashing event is being requested, removing the risk of accidental discharge trigger due to cosmic radiation. The flash rate will be limited by a 30s wait time enforced by the computer.

The flash bulb is mounted to a circuit board with a small reflector. The reflector focuses light into a smaller area limiting the geographical area exposed to the flash, and reducing the amount of power needed to deliver a visible

**Table 1.** Lightcube properties

| | |
|---|---|
| Peak power (W) | 100,000 W |
| Peak flux at 35cm (100-1000nm) | $35kW/m^2$ |
| Pulse length FWHM (ms) | 0.45ms |
| Opening Angle (deg x deg) | 35 x 140 |
| Orbit altitude | 408km |
| Orbit inclination | 35° |
| Range (km) | 408 (closest approach) - 500 (at 35°) |
| V-band flux (at ground during closest approach) | ~4000Jy |
| Apparent Peak V-band magnitude | ~0 |

Note—This table uses lab measured values where possible, otherwise assumes worst case option. Where statistical variation is unknown, fractional error of 20% is assumed.

flash. As the flash is on the external face of the cubesat, it must have a low profile to allow it to clear the cubesat deployer. It must also avoid close metallic contact with the high voltage leads. These and similar design considerations were explored using a ray tracing simulation to arrive at a trough reflector which provides a 35 degree opening angle perpendicular to the long bulb axis. The angular pattern along the axis parallel to the bulb will depend on the cosine of the viewing angle for a FWHM of 140 degrees. Acting as a focus element the flash reflector adds a gain of about 1.5.

The flash tube itself is a linear Xenon bulb which is commonly found in professional camera flashes. The internal arc length is 27 mm and the inner diameter of the quartz glass envelope is 2 mm. The internal gas pressure of 0.5 atm amounts to a small amount of lightly compressed gas in space. Repeated vacuum testing has not exposed any leaks or notable changes in tube performance.

The flash properties are summarized in Table 1. Taken together the distance, reflector gain, and other parameters implies an apparent luminosity of 1e5 W within the field of view. At a closest approach distance of 408km this amounts to a flux of ~4000 Jy or an apparent bolometric magnitude of -2.24.

The Xenon tubes used in Lightcube are similar to those used in commercial flashes, but with a custom driver circuit optimized for space flight. Commercial flashes typically have a spectrum which peaks in the blue and have strong infrared lines, see Fig 3. These flash drivers typically use electrolytic capacitors which are known to energetically disassemble in vacuum. The Lightcube flash driver uses sealed Thin Film Polypropylene capacitors which are rated to withstand vacuum but at some cost to performance. These capacitors have a somewhat lower capacitance and maximum voltage than a typical commercial unit which limits the brightness of the flash. They also have a lower equivalent series resistance which results in higher flash tube current densities. This puts more strain on the tube but does not change the light output.

We have performed lab measurements of a flight-like Lightcube Engineering Design Unit to obtain both the bolometric lightcurve and a spectrum.

Measurements with a Horiba HR-320 monochromator, featuring a holographic grating with 1200 lines/mm, in the visible to the infrared find a spectrum increasing toward the blue. Rising above the bright baseline are several spectral lines associated with Xenon excitation and recombination. The bolometric flux was measured with a calibrated silicon photodiode. The instrument response function, including the grating efficiency, was calibrated against a standard halogen light source. The details of this test, including measurements of calibration sources are reported in a technical memo available on the project web site Goryll (2022).

The bolometric flash light curve shown in Fig 1 peaks at 35kW/m$^2$, decays to 50% within 0.45ms, and is 90% complete by 0.8ms. Measurement of a commercial Canon EX580 flash (Fig 2) found that the Lightcube flash without reflector is roughly 2.5 times dimmer. Though this measurement was done without a reflector, the measurement setup included

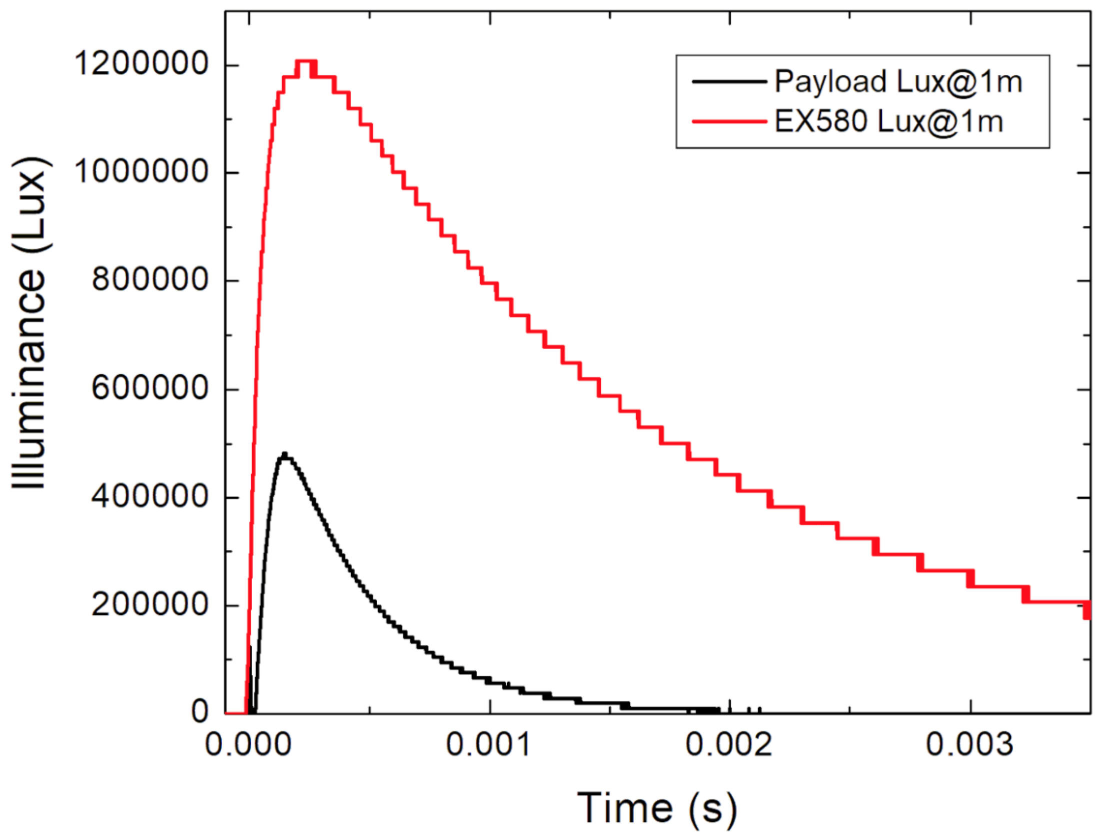


**Figure 2.** Comparison between professional grad (canon EX580) photographer flash and Lightcube without its reflector. In this configuration the lightcube flash is roughly 2.5x dimmer. Addition of a small reflector is being considered to increase brightness if necessary.

significant secondary reflection surfaces amounting to an unknown gain factor. Judging from variation observed during testing we estimate the final flux will be no greater than a factor of 1.5 times higher than this measurement. Final pre-flight measurements with the flight reflector and an anti-reflection enclosure are planned.

The measured spectrum, shown in Fig. 3, has a power law slope increasing towards shorter wavelengths and several emission lines. Comparing to the Canon commercial flash we can see it is consistent with a black body spectrum peaking below 400nm and several spectral lines rising another factor of 2 above the baseline.

### 2.2. *Spacecraft*

Lightcube is a 1U cubesat with a remote controlled flash tube which is designed to be visible to the naked eye. Members of the public will be encouraged to trigger it and observe the flash. The cubesat has been designed to make this process easy for users and tuned to minimize impact on astronomy.

The flash design is very similar to a commercially available camera flash. A Xenon flash tube is driven by a high voltage capacitor. Several changes have been made from traditional terrestrial flashes for operation in space. Charging is regulated so that the final voltage can be adjusted and a discharge circuit has been added to allow the capacitors to be safely unloaded without flashing.

Several challenges and constraints have also influenced the design. The vacuum-safe capacitors used are much larger than those found in commercial units and occupy a large fraction of available volume. Additional challenges include pointing the flash towards Earth and reliably receiving commands from low gain user antennas.

A radio operating in the 70cm UHF band supports uplink commands via DTMF and downlink with a mixture of DTMF and radio teletype (RTTY). The antenna is a custom deployable turnstyle quad. A user with a handheld radio and medium gain antenna operates the spacecraft by dialling a number code using the touch tone pads which are common on most mobile radios, announcing as necessary to comply with amateur regulations. Solar cells charge

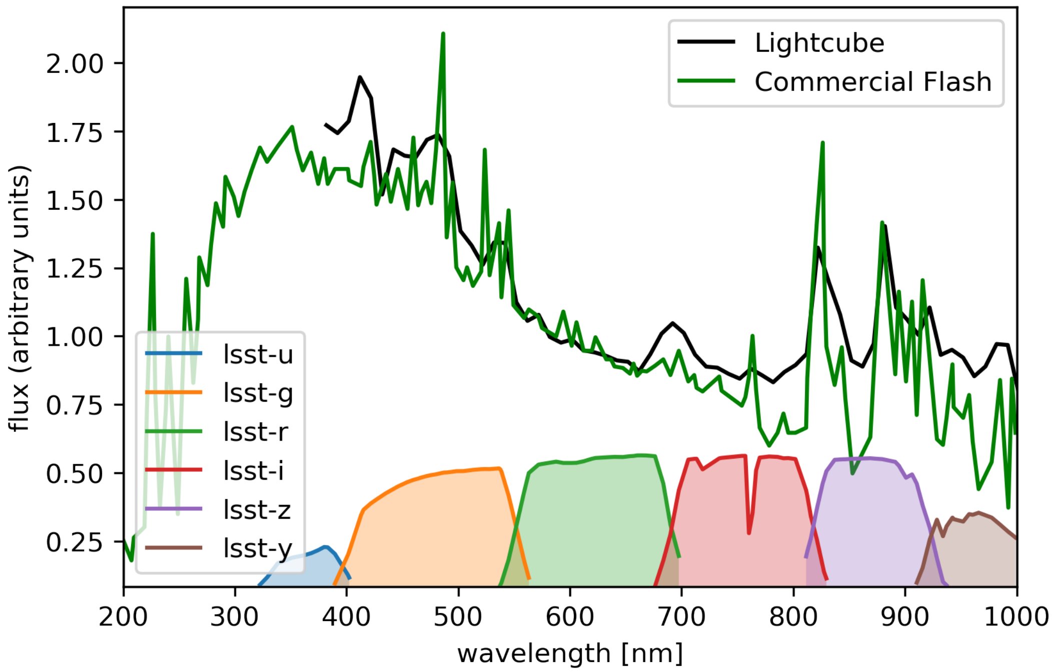


**Figure 3.** Lab measurements of Lightcube engineering design unit xenon flash tube spectrum compared to manufacturer specification. The spectrum is consistent with a blackbody at 8300 K plus several lines, mostly in the near infrared.

rechargeable batteries of the 18650 type. These feed power to the capacitor charging circuit during night time flashing operation. A typical charge can supply current for many more flashes than can be triggered in a typical orbit.

The cubesat geometry and power limitations impose a limit on the number and placement of flash tubes. In the end two flash tubes were placed on opposing faces. After deployment a boom will be released which will cause one of these faces to orient towards earth. This passive orientation system oscillates until damped by energy dissipation in the flexible boom and by interaction with the upper atmosphere. Simulations find this process will likely take days to weeks. Since the spacecraft can come to rest with the gradient arm oriented either towards or away from the earth, both of these sides are equipped with a flash tube. Only the downward facing flash tube will be operated. The direction is identified by IR sensors mounted on both faces.

### 2.3. *Operations*

The concept of operations is designed to be simple for operation by amateur student users. A user will track the spacecraft with one of many freely available satellite tracker phone or computer apps. When overhead, the flash can be triggered via tones transmitted over amateur radio. The spacecraft will respond with a flash and simultaneous UHF radio broadcast containing an audible tone to aid in confirmation of sighting. Time between flashes is limited by the computer to at least 30 seconds. The actual charge time varies depending on battery state and programmed voltage level. As a stretch goal the system will support logging of flash times. This requires the addition of a battery backed real time clock and higher data rate downlink.

Telemetry about the power system, orientiation, software status and flash events are logged to solid state storage. These will be read out during passes over the ASU ground station and posted online. Summary statistics will be encoded in a status beacon which can be received and decoded by amateur operators around the world.

## 3. CLASSIFICATION OF OPTICAL INTERFERENCE

Optical interference due to satellites generally takes the form of reflected solar illumination. These reflections can be specular or diffuse. Specular reflections are caused by smooth surfaces which reflect light in a single direction according to Snell's law. Surfaces which are rough but have a non-zero albedo make a Diffuse reflection where light is scattered in many directions. Lacking losses due to scattering, specular reflections can reflect a large fraction of light incident to

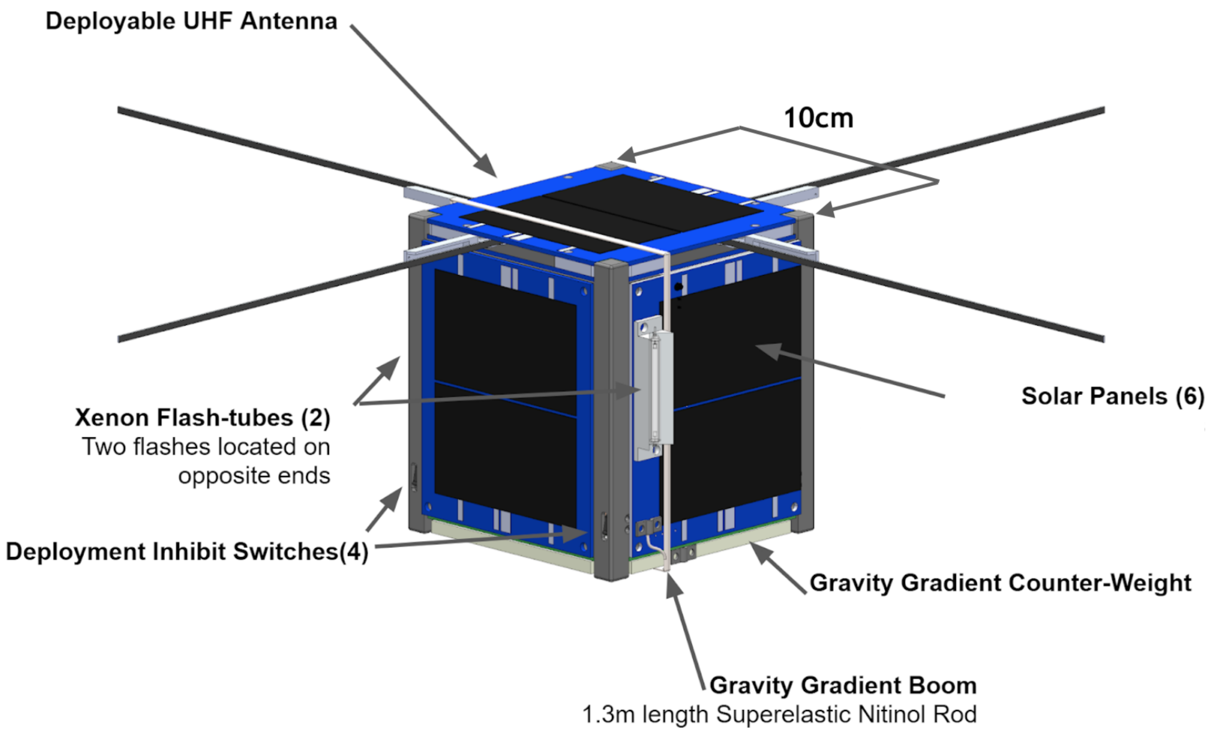


**Figure 4.** Lightcube is a 10cm long cubesat. A gravity gradient boom orients the spacecraft in one of two directions. Xenon flash tubes are located on either of the potential earth-facing sides.

appear very bright but appear only when chance brings them into alignment. Diffuse reflectors have a more uniform radiation pattern making them dimmer but visible from any angle.

### 3.1. *Diffuse Reflectors*

Diffuse reflectors are most visible close to sunset and sunrise when the sun is down on earth but still shining on the satellites. The the number of objects in these orbits has dramatically increase. Since 2017 the number of satellites launched to low Earth orbit (LEO) has increased from 281 to 1322 (Union of Concerned Scientists 2021). New constellations account for a large fraction of these launches with the SpaceX Starlink internet service constellation accounting for 60%. These are early test deployments of small tranches. SpaceX has coordinated spectrum access for at least 42,000 satellites to be distributed over several altitudes, other companies like OneWeb in the UK are aiming for similar numbers. Fully populated, these constellations would have an apparent density on the sky of at least one per square degree. During the summer, parts of the constellation will be illuminated during the night. Photometric and naked eye measurements have found a mean brightness of $m_g$ 4.5. Experimental modifications have tried darker paint on white surfaces which reduced brightness to $m_g$ 6.1 mag. Experimental deployable visors further reduced brightness to $m_g$ 6.5 mag(Mallama 2021), but also show that variation across the range from 4 to 8 due to variation in orbital distance, angle, season and spacecraft orientation is common.

The scale of the impact of sky affected and by the duty cycle. When illuminated, diffuse reflectors are visible from anywhere in view. The space above the northern (and southern) hemispheres is continuously illuminated. Studies of the proposed orbits and observed reflection properties predict the constellation will be a significant change to the night sky, particularly during the northern summer. Scientific astronomical investigations will also see a substantial impact. With a density of greater than one object per square degree even a relatively short widefield observation will contain a bright object and high angular velocities also raise the risk of crossing through long exposures. With its best-in-class combination of wide field of view and sensitivity, the Vera Rubin Observatory LSST program stands to see the greatest impact and has received much study (Tyson et al. 2020).

### 3.2. *Specular Reflectors*

The most famous example of a specular reflector is the original Iridium satellite constellation where chance orbital alignment caused radio antenna panels to reflect sunlight towards the Earth resulting in a moving 10km-wide spot on the Earth which appeared to observers as a brief pulse reaching as bright as -8 magnitude. Many spacecraft, including Starlink nodes, have dimmer specular reflections from patch antennas or other metallic parts. A study by the Evryscope all-sky transient monitor finds a rate of 1800 artificial transients per hour visible brighter than 13th magnitude. Of these, some 300 are likely to the naked eye(Corbett et al. 2020). Meanwhile, observations of Starlink have found occasional specular reflections. These are found to not pose a false positive contamination because the rates are low and orbital positions are generally known (Tyson et al. 2020).

With its single 0.45 ms flashes separated by at least 30s, Lightcube is most analogous to a specular reflector. Notable differences include the fact that the spacecraft need not be in sunlight for a flash to occur and that it is visible across a somewhat wider area. But, for the purposes of comparison to existing impact studies it is more accurate than to compare with studies of diffuse reflectors.

## 4. ASTRONOMICAL IMPACT

The impact on astronomical observations falls into two general categories: 1) corruption of long integrations by introducing bad pixels and 2) triggering false positives in transient searches. As a test case for the impact of LightCube on astronomical observatories we consider the Vera Rubin Observatory (VRO) and its Large Survey of Space and Time (LSST) using an extremely large CCD camera. With its combination of extremely wide field of view, sensitive camera and all-sky transient program it provides a strong limiting case; if the impact on VRO is low, risks to other observatories stand a good chance of being lower.

### 4.1. *Vera Rubin Observatory*

The primary VRO science product will be the Legacy Survey of Space and Time (LSST) which will image the sky once per day much deeper than any past systematic survey. Science goals include identification of near Earth objects, counting supernovae, weak lensing, and many others. The LSST is a significant effort by much of the astronomical community to produce a key research tool which will be used for many years to come.

The VRO, located on Chile's Cerro Pachòn ridge has a 8.4m mirror and 3.2 gigapixel camera giving a 3.5°field of view. Images are recorded every 15s with the telescope following a sky scan pattern optimized to cover the night sky each night while accounting for seasonal variations which illuminate objects within the Earth's orbital plane and other similar factors. Two consecutive exposures are acquired at every sky pointing to provide pairs that can be difference to detect and isolate fast transients. Transients in this category are likely (but not guaranteed) to be objects in low earth orbit or active light sources like airplanes. Images are post-processed automatically to produce alert streams, averages, and other reduced data products.

The rate at which VRO will see a flash from lightcube depends on how often the satellite is commanded to flash by users within range. Most users will have low gain antennas and low transmit power resulting in a low quality link. Additionally 800km wide footprint beneath the satellite is imposed by doppler differences due to orbital velocity offset. Multiple tries might be necessary to trigger a flash. A full simulation of flash rate consider the population of potential users within 400km radius of projected ground tracks for locations visible from the observatory, the restricted opening angle of the flash, path length change through the pass, and similar factors.

We will assume a worse case-scenario of continuously requested flashes leading to a rate-limited 30 s period between flashes. Similarly, although flash brightness will vary depending on range, satellite orientation, and capacitor charge we will set all parameters to acheive a peak V-band magnitude no larger than about -1.5.

The number of flashes from LightCube seen at Vera's site per night depends on how many orbital passes the satellite makes over the site per night. Orbiting at 400km Lightcube will spend approximately half its time over the night side of the planet. Flashing continuously it would log 1440 flashes per 24 hour period. These flashes will be spread out over a wide area as the planet turns beneath the orbital plane. A LEO satellite will make, at most, three passes over any mid-latitude location per night. In this situation one pass transits the zenith taking at most 15 minutes from horizon to horizon. The other passes are shorter and lower across the horizon. Other times the orbital phase is such that the night has two passes equidistant from the zenith. A beyond worst-case estimate is to assume three 15 minute-long zenith passes each night. This amounts to a total of 90 possible flashes in a night. In reality most of these will be occurring close to the horizon where longer path length and higher view angles will mean dimmer flashes.

**Table 1.** LSST band-integrated magnitudes corresponding to both the peak flux and the flux apparent in integrated 15s images.

| filter | band fraction | peak mag | imager mag |
|---|---|---|---|
| lsst-u | 0.0057 | 3.33 | 14.6 |
| lsst-g | 0.0992 | 0.24 | 11.5 |
| lsst-r | 0.0698 | 0.62 | 11.9 |
| lsst-i | 0.0587 | 0.8 | 12.1 |
| lsst-z | 0.0565 | 0.85 | 12.2 |
| lsst-y | 0.0249 | 1.74 | 13.0 |

Flashes will be widely separated. At the closest approach the spacecraft orbiting at 6km/s has an apparent angular velocity of almost a degree per second, yielding a flash separation of 21 degrees. Flashes will be closer together in an angle toward the horizon.

#### 4.1.1. *Conjunction Analysis*

VRO will have a 9.6 square degree field of view with a 3.5 degree diameter. A simplistic model for the LSST observing strategy is to divide the sky into 30s long pointings, divided into two equal length exposures. If a flash conjunction occurs, ie if a flash happens in the field of view, the speed of the spacecraft is such that it will have moved out of the telescope's field of view before the next exposure is acquired.

The rate at which conjunctions occur can be estimated in several ways, but generally always depends on how much time the satellite is visible in the sky on a night. The number of conjuctions is roughly the product of the fraction of the sky covered by the telescope, the number of non-overlapping pointings, and the number of flashes,

$$\text{Number of conjuctions} = \left(\frac{\text{Telescope FoV}}{2\pi}\right) * (\text{Number of pointings}) * (\text{Number of flashes})$$

In section 4 the absolute worst-case number of flashes potentially visible across an entire night, assuming the most pessimistic situation for alignment, flash rate, and similar factors, is estimated to be no more than 90 flashes. Observing continuously through a 12 hour night the LSST program could log 1440 independent visits. This worst case-model predicts VRO conjunction with 76 flashes, or about 5% of visits.

A more realistic estimate made using an orbital propagator to calculate nightly pass trajectories over the observatory, accounting for the restricted flash opening angle, and an estimate for likely user trigger rates would all reduce the predicted flash rate. The trigger range is limited by range and doppler effects to a footprint directly beneath the orbit. During many of the visibility opportunities from Cerro Pachon the satellite will be over the sparsely populated Pacific Ocean or Amazon Basin.

#### 4.1.2. *Flash track*

Is the satellite moving fast enough for the flash to cause a streak? The camera has a pixel size of $0.2''$and the observatory location has an expected seeing of $0.7''$. For LightCube's angular velocity of 0.729 degrees/second, an 0.5 millisecond flash yields a streak of $7{*}10^{-4}$ degrees, or approximately $1''$. A flash will be spread between one to pixels.

#### 4.1.3. *Color magnitudes*

The flash spectrum, as shown in Fig 3, corresponds to a black body with some sub-dominant line emission. This spectrum ($S(f)$) can be used to estimate the fraction ($W$) of total bolometric power (reported in Fig 1) that falls into each LSST filter band.

$$W = \frac{\int S(f) * F(f)}{\int S(f)} df$$

where $F(f)$ is the filter weight spectrum plotted at the bottom of Fig. 3. Most filters will see between 2 and 10% of the total bolometric power. The highest instantaneous brightness occurs in the g band with a magnitude of 0.24.

One important caveat to note is that, due to equipment limitations the laboratory measurements do stop somewhat short of the full range in the UV and infrared. This is handled by truncating the integral. This limits the accuracy of the u and y band measurements.

#### 4.1.4. *Flash Magnitude in Images and potential for nonlinear effects*

The apparent magnitude of a pulse in an image averages down proportionally to the amount of time during the integration that the pulse is on. The Xenon flash curve is approximately 0.45 milliseconds long between half power points. Such a pulse occurring in a 15s integration will appear fainter in the exposure than its peak magnitude by 11.31 mag. Apparent fluxes in integrated images are listed in Table 1 . The brightest is g band at 11.5 mag. This is brighter than the single visit limiting magnitude of 24.5.

If the flux incident on a single pixel is high enough, signal will leak into neighboring pixels along CCD rows. The radius of affected pixels scales with the incident flux but is limited in range by boundaries between CCD chips. This cross-talk can require a large number of pixels to be masked and increasing the amount of data affected. Cross-talk can also have a systematic impact on cosmological programs which look for patterns which vary with size scale. Below a level where detector response becomes non-linear, cross-talk is correctable. In their study of Starlink impact, Tyson et al. (2020) found that objects dimmer than 7th mag contribute cross-talk at correctable levels. The same study also notes that that objects at LEO distances will appear slightly de-focused with a point spread function of $3''$distributing flux over more pixels and further reducing cross-talk levels.

Lightcube flashes are bright enough to rise above the image noise but not so bright as to cause saturation problems. Next we must consider whether the appearance of the Lightcube source in an image poses a contamination issue for the downstream science.

#### 4.1.5. *Presence in Flagging and Alerts*

The LSST is a transient program targeting events slower than one minute. At each pointing visit, two 15s images are recorded (Abell et al. 2009, Ch1). These are differenced to detect cosmic rays (Abell et al. 2009)[2]. Cosmic rays reach ground-based CCDs in the form of secondary particle shower products which can be distinguished by amplitude and morphology. These electrons, muons and other secondary particles with a range of energies produce a variety of shapes in images ranging from single pixels to lines and curved tracks(Bosch et al. 2017). Flashes appear as 11th magnitude sources with PSF slightly wider than a point source at infinity. It is not known whether such a morphology would be classified as a cosmic ray. This will likely depend on a balance between LSST science cases and those attempting to search for fast transients in the visit differences.

Any area not flagged in the visit differencing is a potential detection. The flagged images are differenced against a reference image of the sky location. Any $5\sigma$ detection is reported as an event; a so-called DIASource. With a predicted astrophysical event rate of 1000/sq deg/hour the survey is expected to produce millions of events per night (Jones et al. 2018). These are analyzed by science specific pipelines to search for coherent orbital tracks, emerging supernovae, and previously unknown astrophysical phenomena. At each of these stages further classification is done on the basis of metadata, historical trends, known objects, and more.

## 5. ANALYSIS AND CONTEXT

Turning all parameters to their worst case we can expect to see no more than 75 flashes per night in LSST images. These will be at most 11th magnitude and appear in one of the two 15s consensus image pairs. Flux is further diluted by a an out-of-focus effect but this has not been accounted for here. Occurring in only one of two frames the detections will likely be flagged as cosmic rays but this will depend the range of cosmic ray morphologies flagged. If the events are not flagged Lightcube will contribute at most 75 events to the LSST event stream which expected to produce millions of events per night.

To LSST, Lightcube will be most similar to a series of faint (just barely naked eye visible) specular reflections. Such reflections are commonly observed by widefield transient observatories. In a 2020 survey by Evryscope for specular

[2] The LSST Science book also mentions using differenced images to detect fast moving solar system objects, however we have not yet been able to find further details on this plan. The known orbital positions of LightCube should be sufficient to prevent mis-identification with other potential solar system objects.

reflections that could be tied back to spacecraft found $340^{+150}_{-85}$ per sky per hour brighter than a limiting magnitude of 4 and 1800 brighter than $m_g$ of 13 Corbett et al. (2020). These were found to contribute a negligible source of false positives to science programs like the search for prompt emission associated with Fast Radio Bursts.

Meanwhile projections of astronomical impact posed by constellations have considered specular flashes as well as diffuse (Tyson et al. 2020). A pessimistic prediction assuming each satellite in every constellation in orbit in 2020 were to emit one Iridium-bright flare per day arrives at a prediction of some 660 flares per night above the horizon. These flares are much brighter (-4 to -8 mag) than Lightcube and at lengths of seconds, do not integrate down in long exposures. Such flashes are bright enough to form internal reflections, cause saturation, and uncorrectable cross-talk leading to loss of entire images. However, given the relative rarity the impact is judged to be much less than the net impact of streaks. In collaboration with the VRO and other astronomers SpaceX has trialled several mitigation strategies. Reduction of specular reflections is not a focus of that effort.

## 6. ASTRONOMICAL IMPACT MITIGATIONS

Despite the apparently low impact on VRO, and by extension other less sensitive observatories, the project team is taking several steps to monitor or mitigate any potential impacts. These include adjusting the spectrum to minimize infrared lines, logging and publishing flash occurrences, and tuning the output power to the minimum needed for human perception.

## 7. HUMAN PERCEPTION OF LIGHTCUBE

Lightcube was designed to be seen by unaided human eyes. Generation of a light bright enough to be seen by humans from a 10cm cube in orbit is a challenging goal. Previous attempts in this area have produced, at best, sources requiring binoculars and long integrations to see; a flash has not been attempted. Nearly every design variable from the spacecraft attitude to the radio link have been assumed to be at peak performance. In reality these will all vary; even in the best case the flash will most times be dimmer than the brightness projections above.

The human perception of a short light pulse is also an important factor. The flash, like a typical camera flash, releases most of its power in ≈1ms, however, the human eye integrates incident light over 20 to 100ms depending on light levels. Just like in a camera exposure, a short light pulse is perceived as darker compared to a longer light pulse of identical peak intensity. The dark adapted eye uses only the rods which have a time integration effect which will further average down. Flashes are much easier to see when they are bright because the photopic response of the cones is much faster. Estimates for human perception of the pulse on orbit range as high as 4 and as low as 10 depending on these various factors. Seeing Lightcube will require some persistence and planning.

## 8. CONCLUSION

The Lightcube student project aims to produce a naked eye flash triggerable by anyone. This is a challenging task which has never been tried before and the many factors add up to a stiff challenge for the students. Here we have attempted to estimate the potential impact on astronomy. Wherever uncertainty remained we used the worst case parameters. With its combination of depth and widefield sensitivity VRO presents a strict test case. Rather than attempting to model the number of triggers occurring over VRO we assumed the maximum possible. Much of the tracks will be over sparsely populated land or ocean; triggers over VRO (and many of the worlds isolated observatories) will be rarer than we assumed in this analysis. Even when flashes occur in frame, the impact is dramatically reduced by the integration time and automated flagging routines. These mitigations are not unique to LSST, coincidence imaging and automatic flagging routines are essential for any large survey.

The laboratory measurements and analysis in this paper provide technical detail but potentially overcomplicate the situation. The essential picture is of a slightly dimmer than usual professional camera flash at 400km. This is a very long range. The shortness of the flash means it will likely appear fainter to the human eye than the peak power suggests. There are many brighter such flashes from reflections off of bright objects happening all the time. The only difference in this case is, one will know where to look!

Though Lightcube, and any small student cubesat project like it, is extremely difficult. The concept and is appealing for its simplicity and forms a powerful attraction to people. If it works as intended many people who might never have done so will have gone outside and looked up.

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