Title: CubeSat amateur laser communicator with Earth to Moon orbit data link capability

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Need

Available bands [1] at 2.4GHz and 5.8GHz for amateur satellite communication are increasingly crowded. Higher frequency amateur bands meanwhile require uncommon microwave parts to implement transceivers, and working with 10 GHz or above require electric power typically not available in CubeSat. Therefore, to enable amateur Moon exploration, amateur laser communicator built of common, low-cost parts will help to extend amateur satellites operating range up to at least moon orbit.

Mission Objectives

Mission objectives (sorted by descending priority):

1) Development of amateur laser communicator for Cubesat achieving 100 kilobit total data transmission in both uplink and downlink.
2) Development of CubeSat 3U chassis capable of holding laser communicator and establishment of successful 2-side contact while in orbit, with at least 10 interactive telemetry and command session per orbital pass.
3) Successful automated tracking of CubeSat by ground station based on wide-field camera, with position in 500km altitude orbit estimated with error below 2km.
4) Autonomous position and attitude determination and control of CubeSat by the means of camera used in laser communicator, with attitude control accuracy 0.02 deg.
5) Establishment of downlink using laser communicator while flying trans-lunar orbit, at distance of at least 400000 km.

Concept of Operations

The operations utilize the following non-standard approaches to save development time and cost:

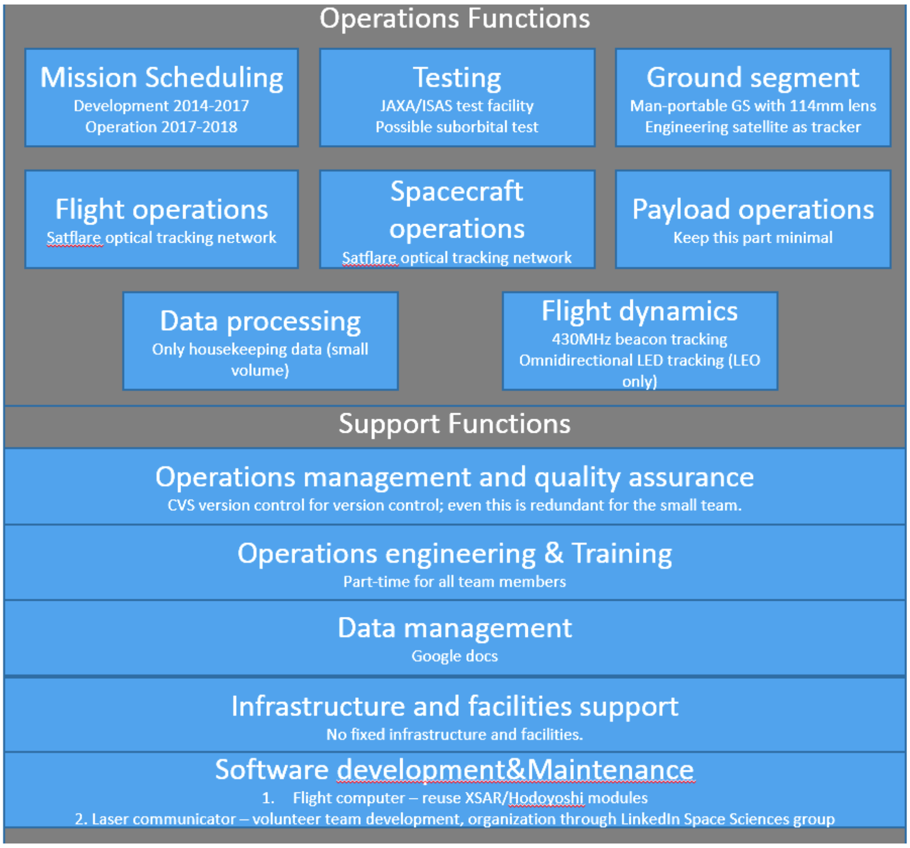
1st, engineering satellite model will double as ground station for both radio and optical tracking.

2nd, usage of volunteer staff to help in software development and tracking

3rd, man-portable ground station to be installed in varied locations according to weather forecasts and expected ground track of satellite

4th, usage of industrial DC servo motors without external flywheel for the role of the reaction wheels

5th, usage of same camera for attitude determination and laser communication. Such method allows significant (by factor of 2) relaxation of the pointing accuracy requirements by easily calibrating alignment errors.



Operations Functions

Mission Scheduling
Development 2014-2017
Operation 2017-2018

Testing
JAXA/ISAS test facility
Possible suborbital test

Ground segment
Man-portable GS with 114mm lens
Engineering satellite as tracker

Flight operations
Satflare optical tracking network

Spacecraft operations
Satflare optical tracking network

Payload operations
Keep this part minimal

Data processing
Only housekeeping data (small volume)

Flight dynamics
430MHz beacon tracking
Omnidirectional LED tracking (LEO only)

Support Functions

Operations management and quality assurance
CVS version control for version control; even this is redundant for the small team.

Operations engineering & Training
Part-time for all team members

Data management
Google docs

Infrastructure and facilities support
No fixed infrastructure and facilities.

Software development&Maintenance
1. Flight computer – reuse XSAR/Hodoyoshi modules
2. Laser communicator – volunteer team development, organization through LinkedIn Space Sciences group

Figure 1. Proposed Mission Operations Functions.

Key Performance Parameters

Success criteria of an amateur communicator on board of Moon-exploration satellite are the follows:

1) Be neither licensed nor limiting number of users using communication channel. Laser communicators, with their excellent spatial multiplexing capability, perfectly fit this role.
2) Has the size allowing integration into the 3U CubeSat – the de-facto maximal size of satellite affordable to amateur operators.
3) Must provide at least 10 bit/s (decoded) downlink rate (equivalent to 1 photo sent per day) at Moon orbit to be still useful for exploration and entertainment.

Space Segment Description

The technical feasibility analysis and preliminary engineering of 3U CubeSat-mountable laser communicator, capable to communicate up to Moon distance was done. All principal components are commercially available and listed below:

- 0.1W, 650nm, 0.5mrad divergence laser pointer
- STAR250 CMOS sensing array (both on uplink and downlink)
- 43mm wide-angle CCD lens assembly (for tracking and uplink)
- 100-200mm aperture amateur telescope (for downlink only)

Below is the detailed link margin calculation sheet. On left is the tracking/uplink mode, on right is the downlink mode. All in all, **at Moon distance downlink up to 10 bps** is possible after taking into account camera noise, saturation, nightglow, encoding to reject starlight, and all system losses. Data rates up to **160 kbit/s will be possible for 500 km LEO** operation as well.

Table 1. Detailed communication budget of the proposed laser communicator.

	tracking/uplink	downlink
Peak power available, W	*0.83*	*0.83*
LED luminous effciency, unitless	0.12	0.12
LED directivity, unitless	5.00E+07	5.00E+07
Communication distance, m	400000000	400000000
Power density before atmosphere, W/m2	2.47684300993125E-012	2.47684300993125E-012
Atmospheric transmission	0.7	0.7
Camera transmission to pixel	0.8	0.8
Nightglow, watt/steradian	6.40E-07	6.40E-07
Pixel array size	262144	262144
Field of view, degrees	83	2
Camera aperture, m	*0.043*	*0.2*
Signal on pixel, W	1.0071271875E-015	2.17875E-014
Nightglow on pixel, W	3.01E-14	3.78E-16
Camera quantum efficiency	3.50E-01	3.50E-01
Single photon energy	3.74897E-019	3.74897E-019
Electrons/watt	933589759320560000	933589759320560000
Signal-related flow, electrons/s	940	20340
Nightglow related flow, electrons/s	28073	352
Dark current, electrons/s (STAR 250 specs)	4750	4750
Electron noise, electrons	76	76
Orbit altitude, km	400000	400000
Orbital speed, m/s	989.6740792088	989.6740792088
Worst case apparent speed, m/s	26980.1653628855	26980.1653628855
Maximal angular speed, rad/s	6.74504134072138E-005	6.74504134072138E-005
Maximal imaged speed, pixel/s	0.0237165405	0.9842364324
Minimal pixel integration time, s	42.1646655542	1.0160160375
quantization, electrons/LSB	35	35
Maximal pixel level	1024	1024
Dark pixel value, saturation uncorrected	**39542**	**148**
Signal pixel value, saturation uncorrected	**40674**	**739**
Average dark level limit , ADC counts	921	921
Saturation-limited mode bit-rate multiplier	44.1628664495	1
S/N, dB	**10.68**	**10.33**
Encoding ratio to reject starlight	0.5714285714	0.5714285714
Shrink ratio to avoid sub-pixels (0.7 if C32<=1)	1	0.7
Average pass duration, s	15265.2395211932	15265.2395211932

Average downlink/pass, bits	**9136**	**150246**
Nightglow margin (5=average pollution)	**5**	**5**
Maximal bits/frame at ideal conditions	3	2
Data rate, BPS	**0.598**	**9.842**
Optical filter effective bandwidth, nm	400	400
Optical filter transmission at center	0.5	0.5
BER	**0.0006138165**	**0.0010109191**
Erroneous bits/pass	5.00	151.00
Data rate multiplier (downlink only)		25
Dark pixel value, saturation corrected	895	5
Signal pixel value, saturation corrected	921	29

In addition to optical communication, backup 430 MHz omni-directional radio will be available for tele-command and telemetry. The tentative 3D model of the spacecraft is shown on the Fig. 2 below.

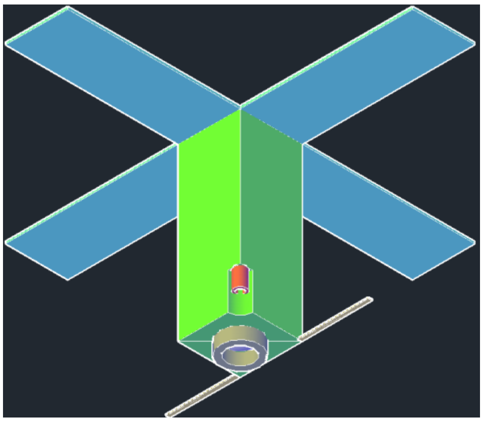


Figure 2 Tentative 3D view of the proposed satellite.

Orbit/Constellation Description

Because the mission will demonstrate communication mode rather than provide actual communication service, a wide range of orbits can be accommodated:

- Trans-lunar, highly-elliptical orbit or GTO. Allows full test of spacecraft capabilities
- Any low-earth orbit. Allows test of most capabilities, except for extremely long-range communication link.
- Suborbital test. Same as before, but less interactive, as all tests must be done rapidly in automated sequence before reentry. Cannot test long-range communications. Also, likehood of software-related failure precluding full test of communication capabilities is greatly increased, because updates would be not available.

Implementation Plan

To build a CubeSat rapidly and without crises, work team must be as small as possible. According to established practices (see SMAD book [2]) in space community, around 6 major collaborators and no more than 15 minor collaborators can be accommodated safely in informal organization framework. The tentative collaborators and their roles are summarized in Table 2.

Table 2. Tentative collaboration framework for the proposed satellite.

Collaborators	role	Level of contribution
Saito`s lab (JAXA)	laser, system integration, test	40%
LinkedIn Space Science group volunteers	programming	20%
Maenaka lab (Hyogo University+ Keio)	Sensors and flight computer	25%
Satflare optical tracking community	Satellite tracking	2%
SOCRATES team (AES) – review	review	5%
Interorbital Systems	testing	3%
Fuke`s lab (JAXA)	testing	5%

Table 3. Estimation of the life cycle cost and schedule of the proposed mission

Part of mission	start	deadline	Cost, USD
Feasibility study	4/2014	7/2014	0*
Satellite bus and standard parts (Pumpkin)	7/2014		50000
Reaction wheels (DIY from Maxon motors)			5000
Camera parts and sensors (Misumi+STAR250)			18000
PCB manufacture (P-ban)			1000
Lasers, focusing and jigs (Hitachi, g-labs)			3500
Glue functions space-rated FPGAs (Atmel)			1600
Ground station telescope with tracking		5/2015	2800
System integration, engineering model	8/2014	5/2015	13000
System integration, flight model	5/5015	7/2015	4500
Ground testing	6/2015	6/2017	0*
Software	9/2014	9/2017	0*
Launch	12/2017		160000**
Mission support	12/2017	2/2018	9000
Budget overrun margin of 25%			67100
Total budget (worst case)	4/2014	2/2018	335500

*some parts of mission made on volunteer and part-time job basis are assumed to be free of cost

**may be for free if JAXA will cooperate in launch service (unlikely)

Major project risks (technical or programmatic)

- Failure to provide attitude control of required 0.02deg accuracy
- Failure to obtain planned sensitivity of laser receiver because of unanticipated noise sources
- Failure to secure launch vehicle for the trans-lunar or geostationary transfer orbit
- Failure to acquire required financial support to purchase software or launch
- Failure to obtain JAXA permit for international cooperation

References

[1] Frequency Allocation Table Table-2 (27.5MHz-10000MHz) http://www.tele.soumu.go.jp/resource/e/search/share/2013/t2.pdf, accessed 26 June, 2014

[2] James R. Wertz, David F. Everett and Jeffery J. Puschell, "Space Mission Engineering: The New SMAD", published by Microcosm Inc, 2011, ISBN 978-1-881-883-15-9, pp. 753-779