

A satellite view of Earth from space, showing a portion of the African continent and surrounding oceans. The image is used as a background for the presentation slide.

cote

Software Simulation of the Space Environment

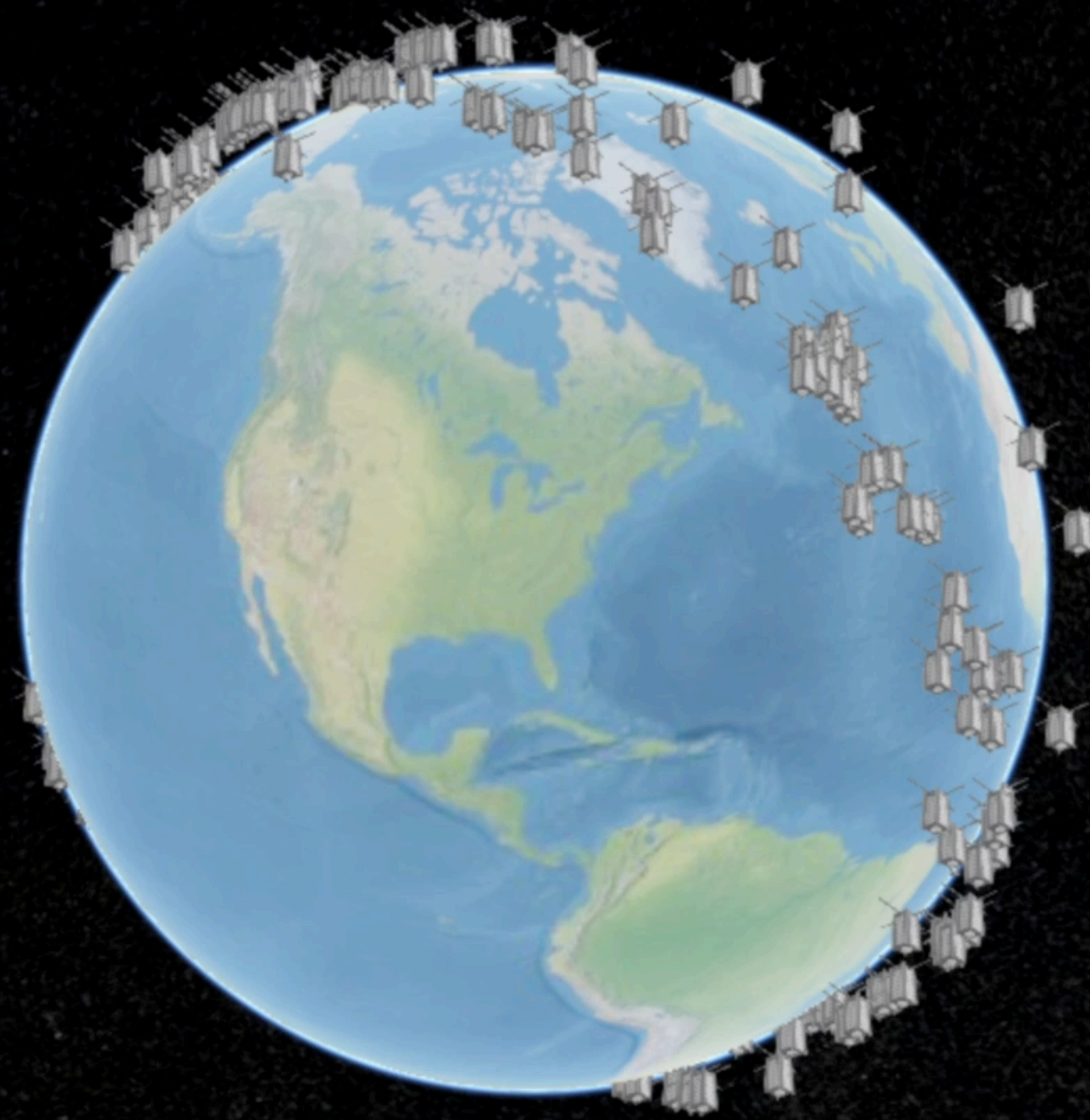
Brad Denby, bdenby@cmu.edu

Advisor: Brandon Lucia, blucia@andrew.cmu.edu

<https://github.com/CMUAbstract/cote>

Carnegie Mellon University

Simulating Existing Constellations

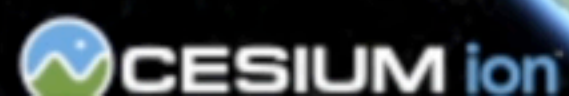


60x
Nov 1 2019
22:12:52 UTC

Simulating New Deployments



60x
Nov 1 2019
22:54:27 UTC



Overview

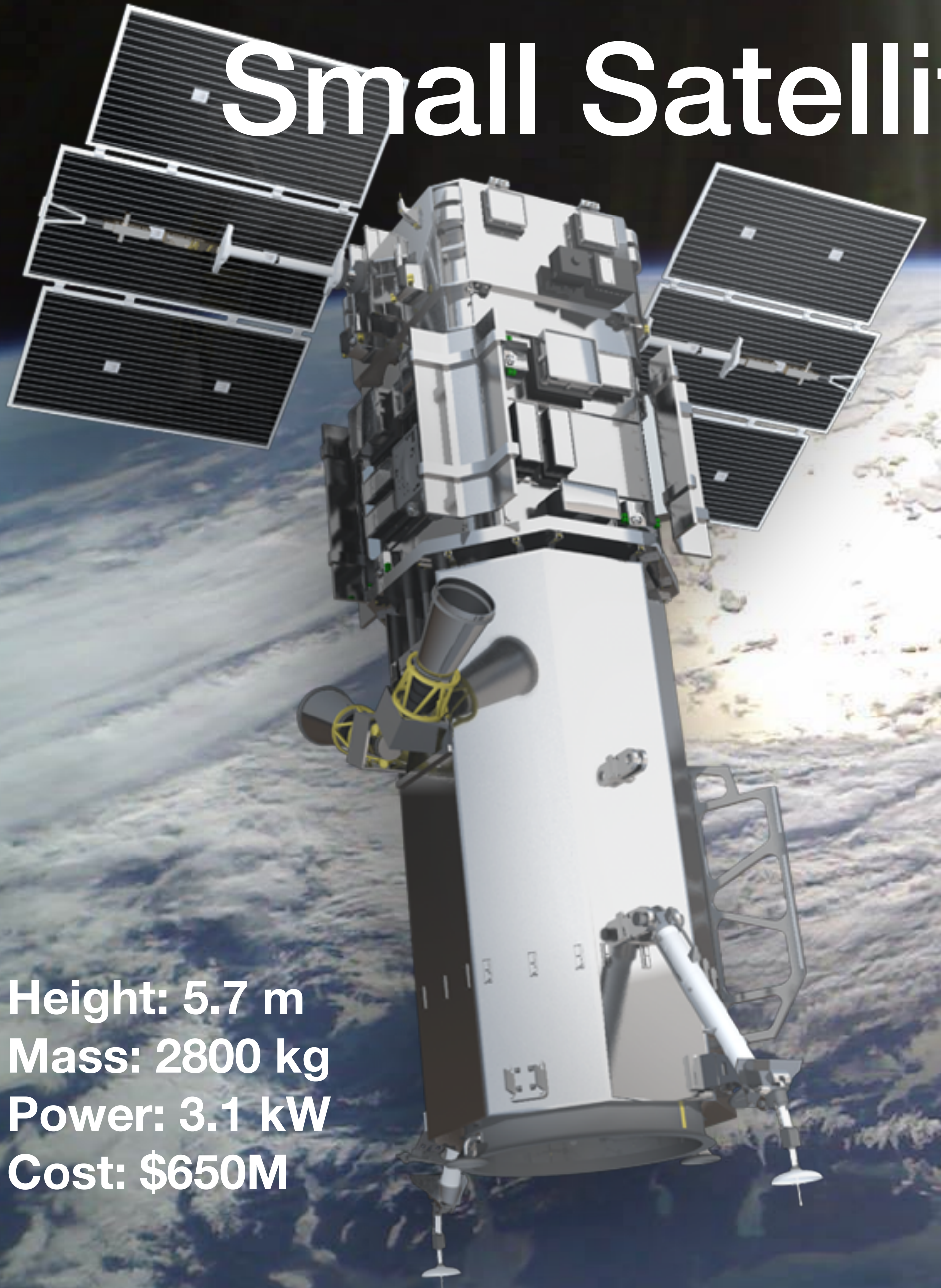
Background and Related Work

Components of Space Simulation

The cote Workflow

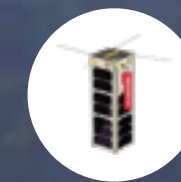
Example Programs in cote

Small Satellites Support Innovation



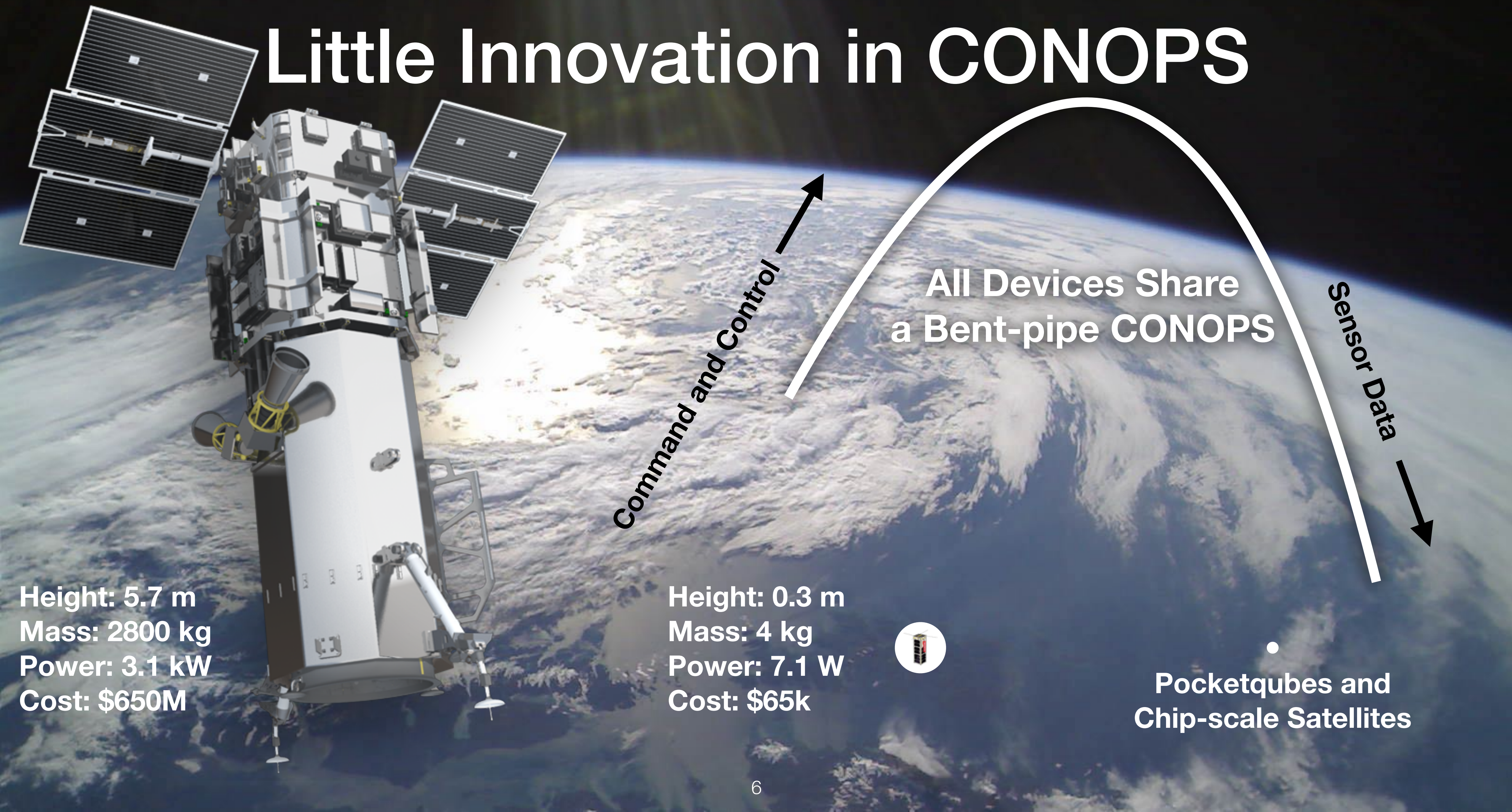
Height: 5.7 m
Mass: 2800 kg
Power: 3.1 kW
Cost: \$650M

Height: 0.3 m
Mass: 4 kg
Power: 7.1 W
Cost: \$65k



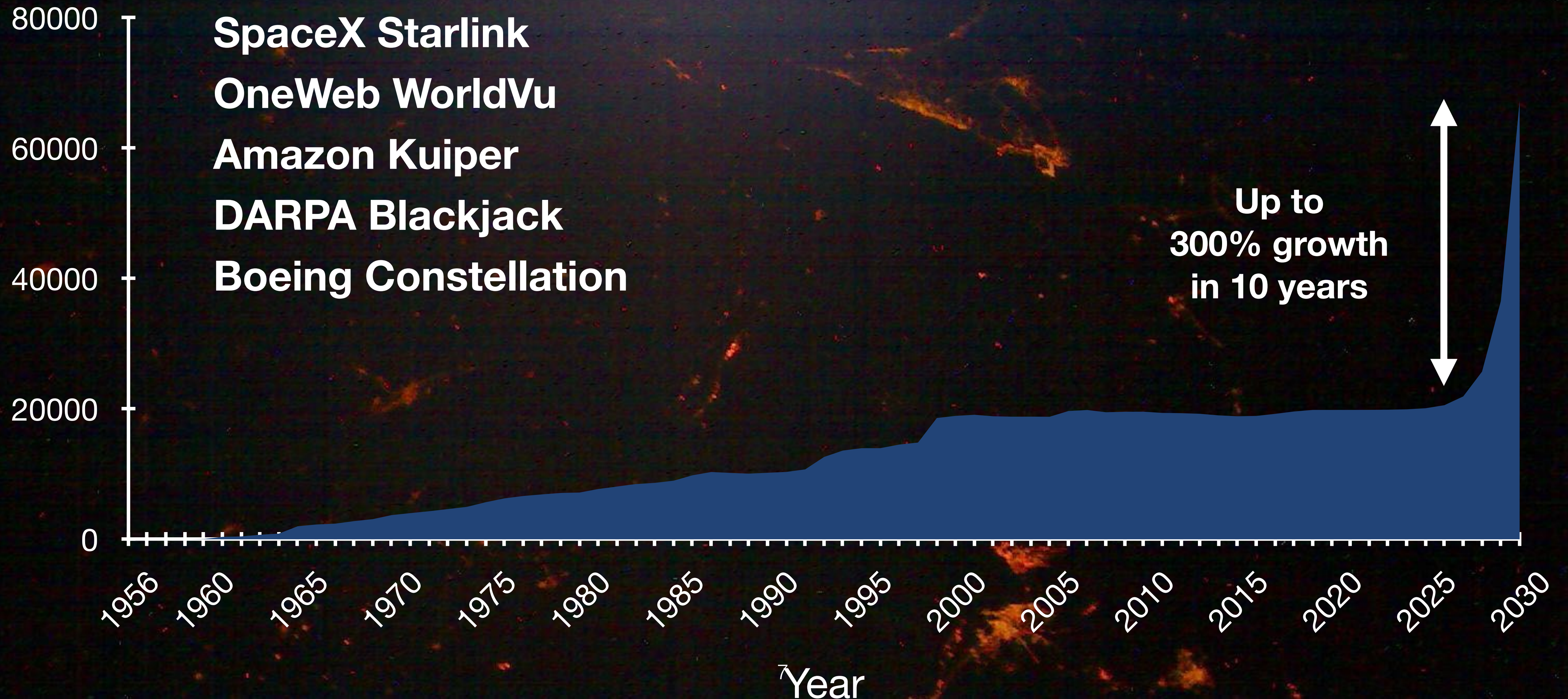
•
Pocketqubes and
Chip-scale Satellites

Little Innovation in CONOPS



CONOPS Must Change

Satellites Orbiting Earth



Downlinking Data Does Not Scale



Downlinking Data Does Not Scale



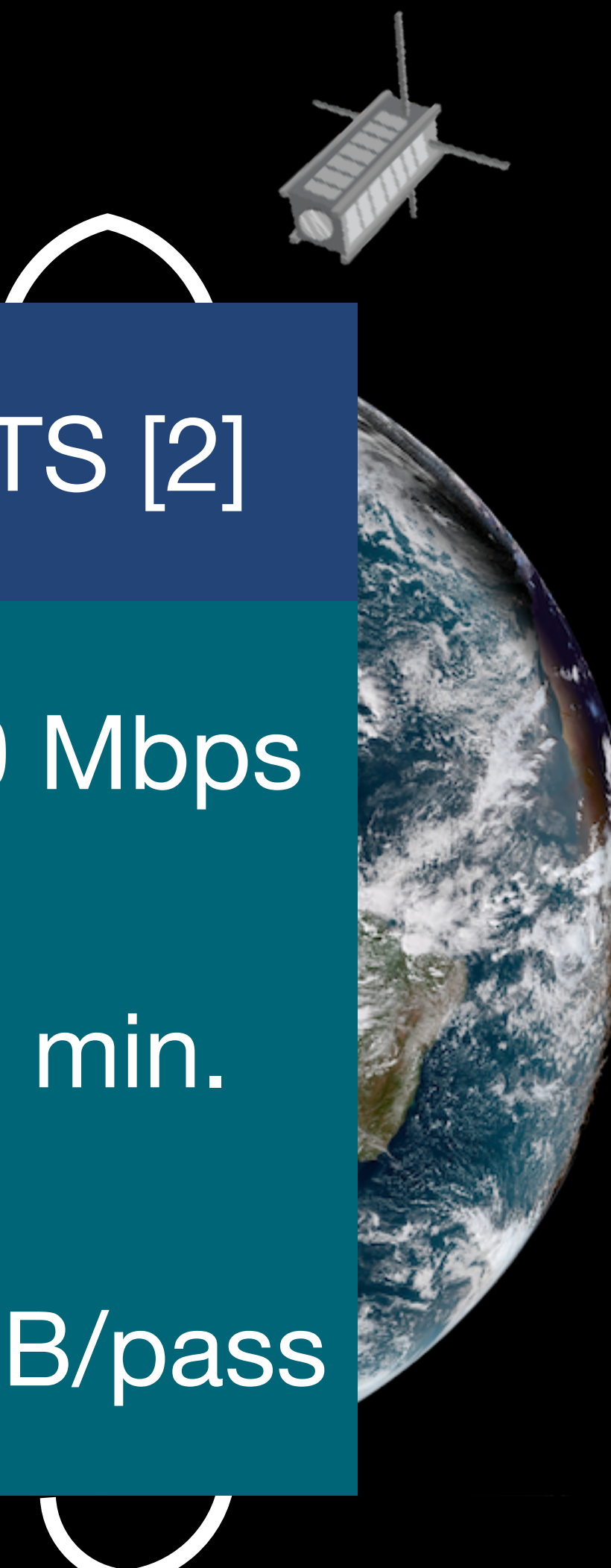
Downlinking Data Does Not Scale

Enterprise [1]	
Bitrate	200 Mbps
TX Duration	<10 min.
Data Down	15 GB/pass



[1] Dove High Speed Downlink System

Downlinking Data Does Not Scale

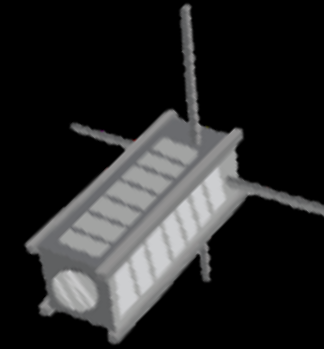


	Enterprise [1]	COTS [2]
Bitrate	200 Mbps	<120 Mbps
TX Duration	<10 min.	7-8 min.
Data Down	15 GB/pass	5.3 GB/pass

[1] Dove High Speed Downlink System

[2] cote Simulator: <https://github.com/cmuabstract/cote>

Downlinking Data Does Not Scale

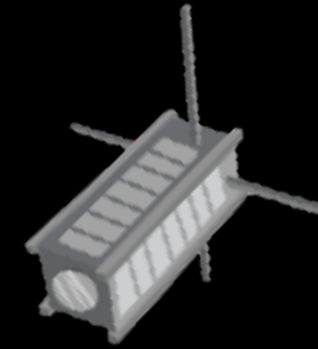


	Enterprise [1]	COTS [2]	Near Future
Bitrate	200 Mbps	<120 Mbps	1 Gbps?
TX Duration	<10 min.	7-8 min.	10 min.
Data Down	15 GB/pass	5.3 GB/pass	75 GB/pass

[1] Dove High Speed Downlink System

[2] cote Simulator: <https://github.com/cmuabstract/cote>

Downlinking Data Does Not Scale

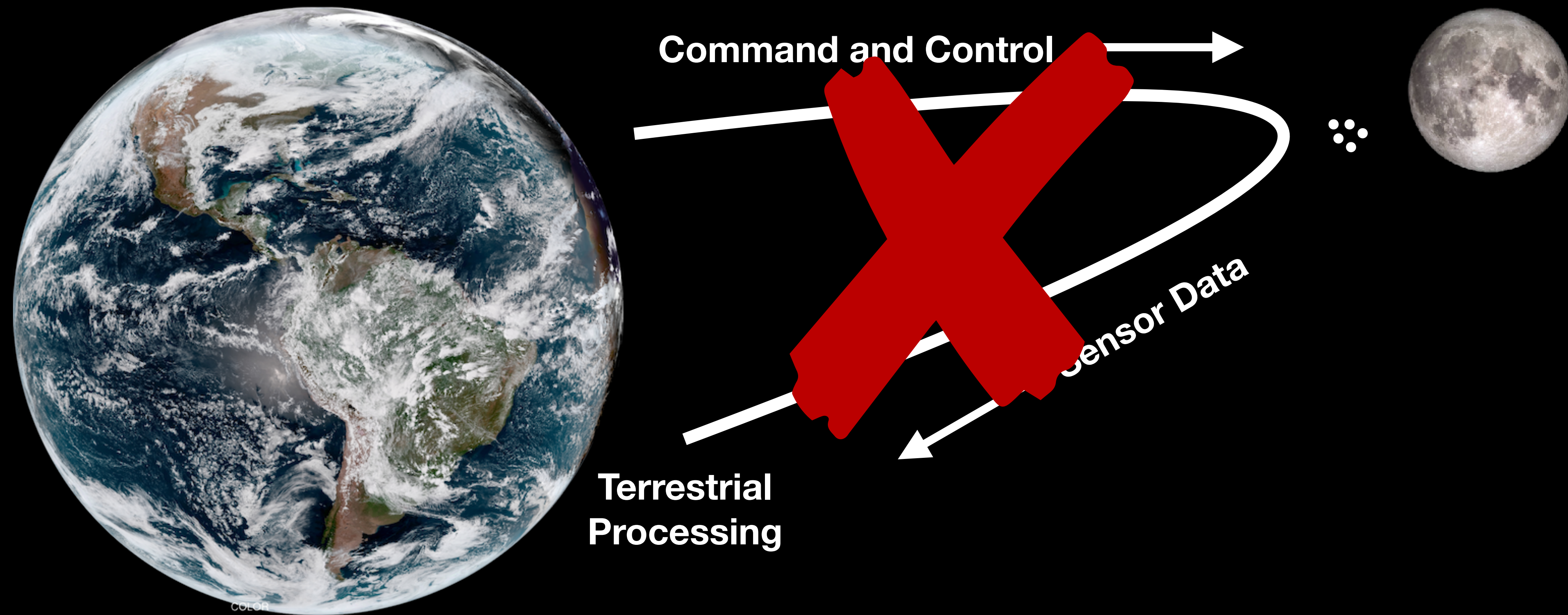


	Enterprise [1]	COTS [2]	Near Future	Mega Constellation
Bitrate	200 Mbps	<120 Mbps	1 Gbps?	No Change
TX Duration	<10 min.	7-8 min.	10 min.	↓(contention)
Data Down	15 GB/pass	5.3 GB/pass	75 GB/pass	Less per sat.

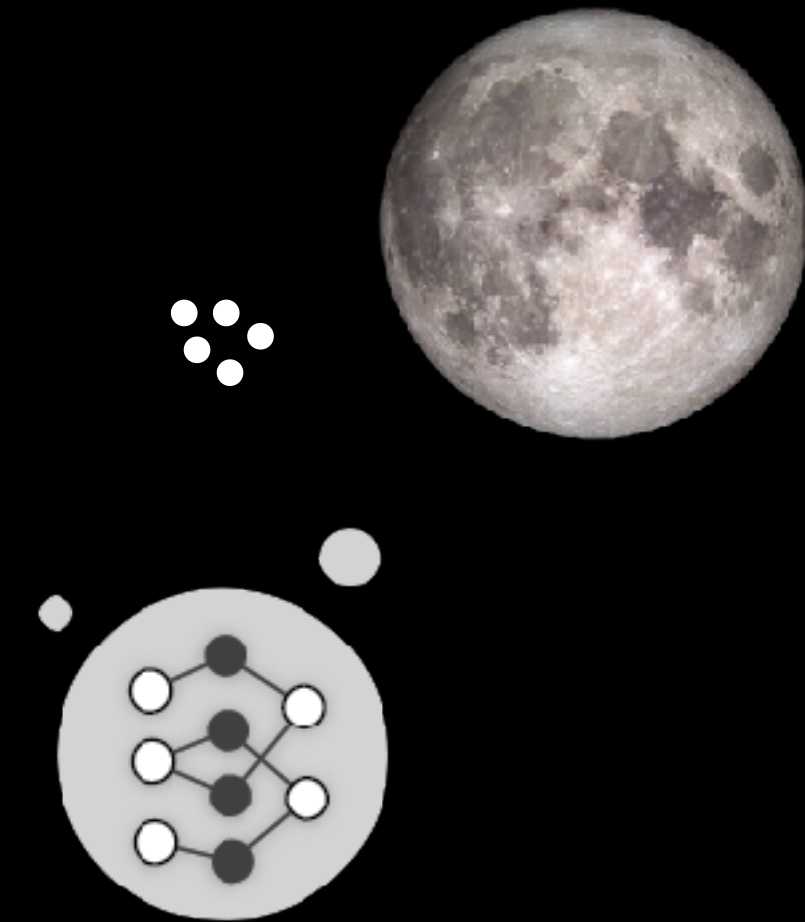
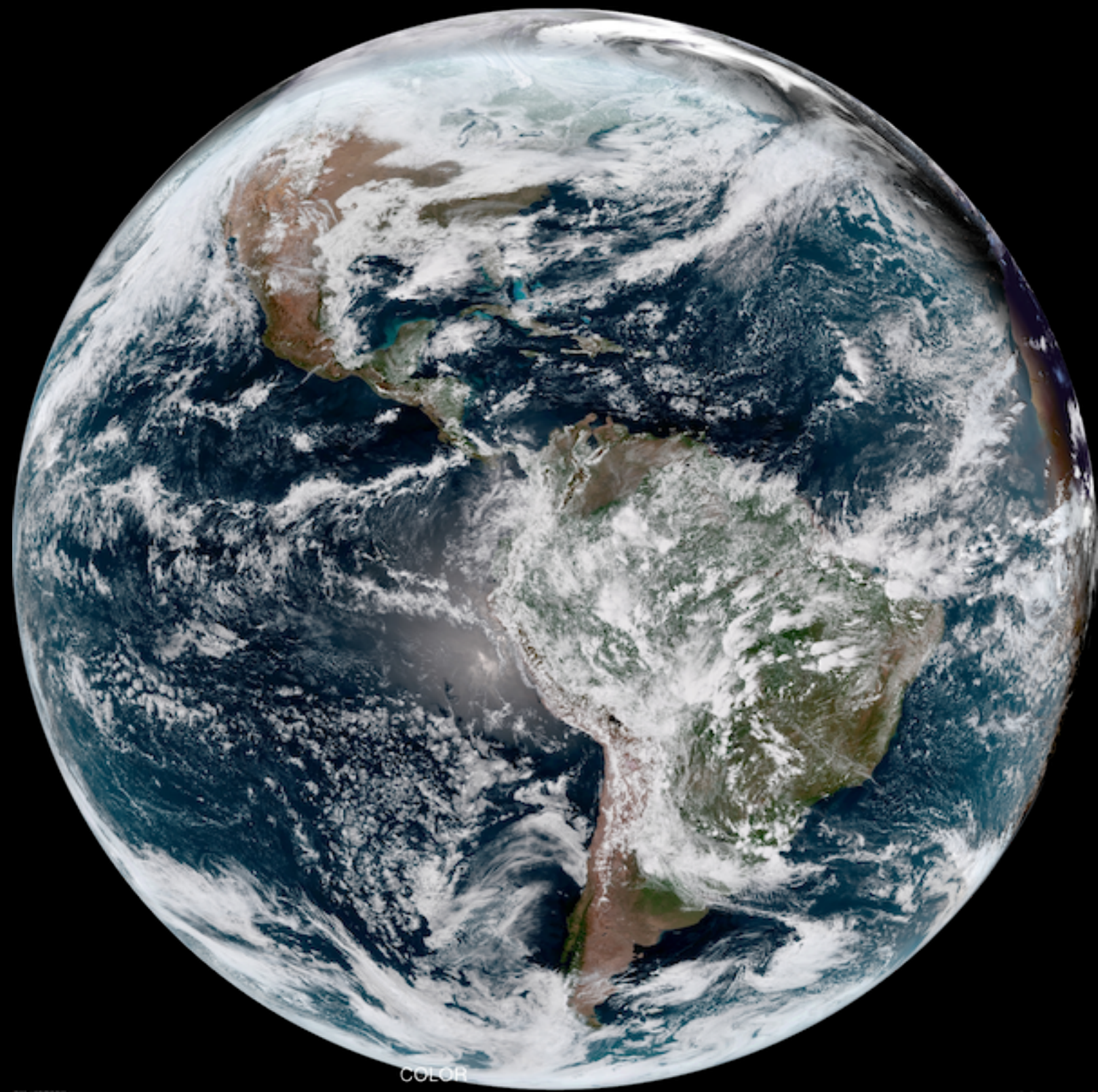
[1] Dove High Speed Downlink System

[2] cote Simulator: <https://github.com/cmuabstract/cote>

Reducing Reliance on Bent Pipes

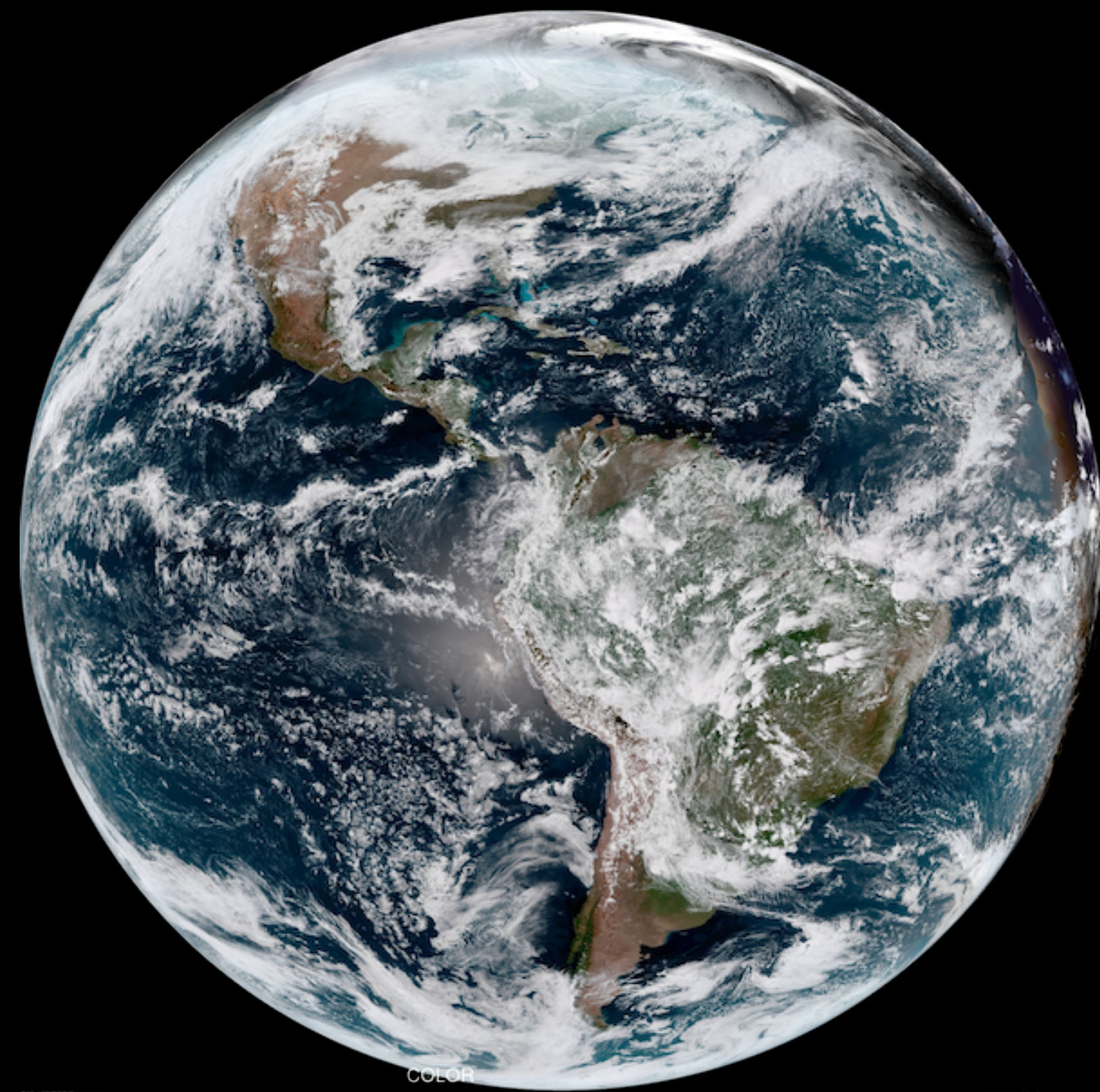


Edge Computing: A Scalable Alternative

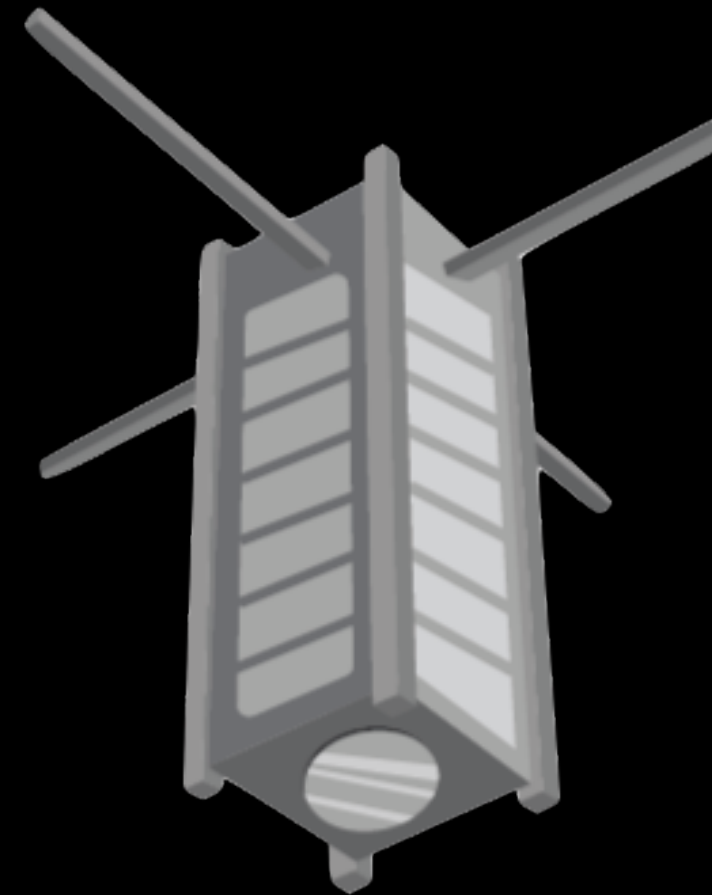


**Computing
at the Edge**

Edge Computing: A Scalable Alternative



Existing Systems



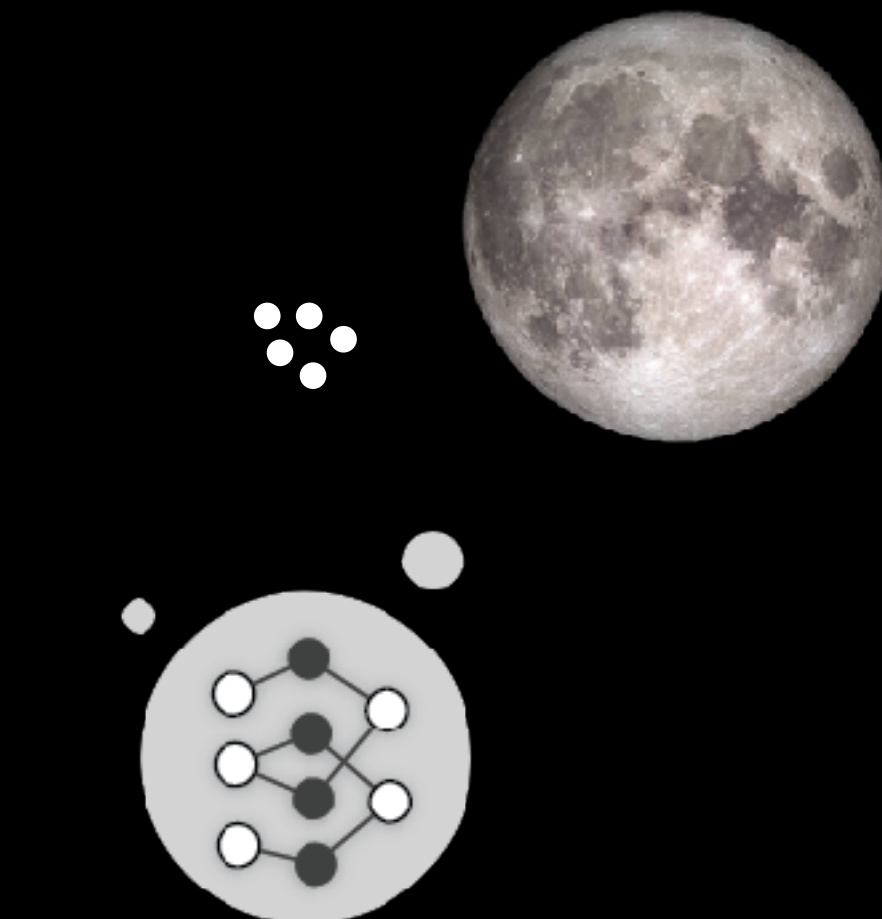
Communication

Guidance,
Navigation,
& Control

Sensors

Edge Computing in Space

e.g. Embedded Compute Module



Computing
at the Edge

Overview

Background and Related Work

Components of Space Simulation

The cote Workflow

Example Programs in cote

Computational Nanosatellites

Machine Learning in Space



Machine Learning Bridges the Gap

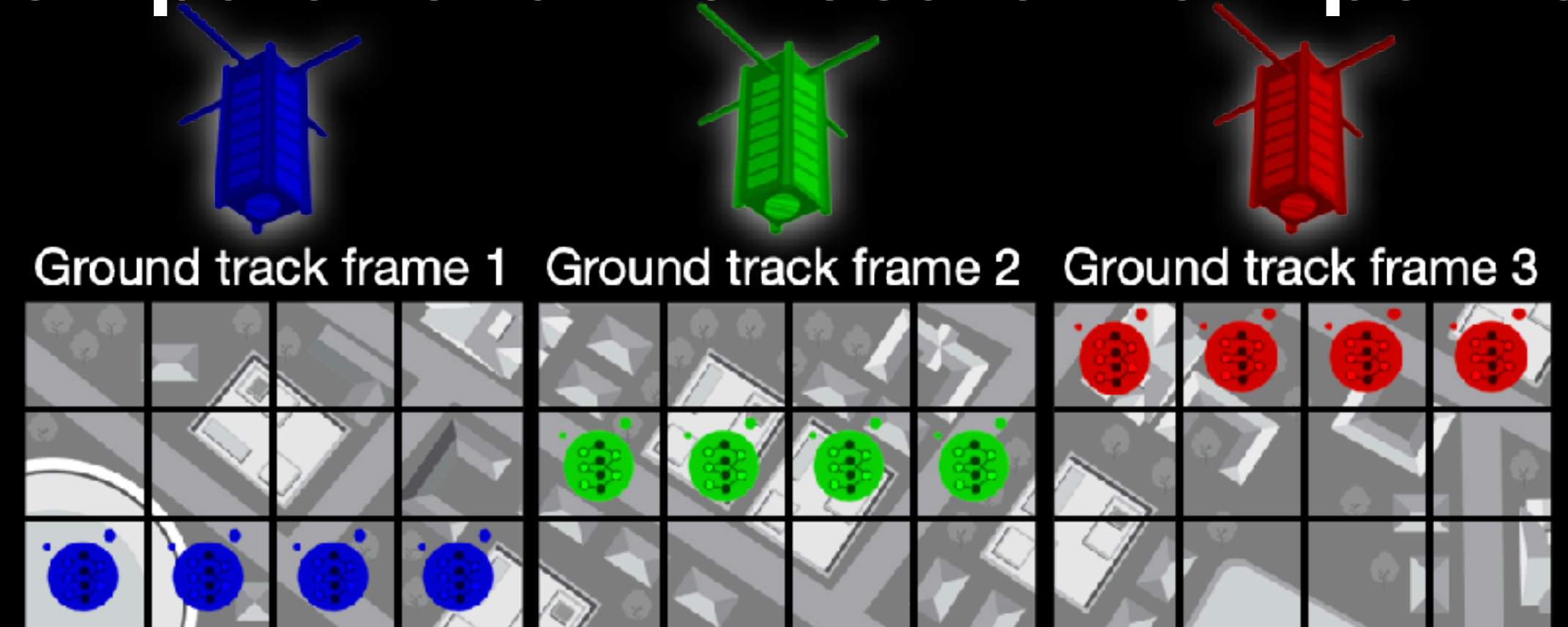
Orbital Edge Computing: Machine Inference in Space
(CAL'19; B Denby, B Lucia)

Computational Nanosatellites

Machine Learning in Space



Computational Nanosatellite Pipelines



Machine Learning Bridges the Gap

Orbital Edge Computing: Machine Inference in Space
(CAL'19; B Denby, B Lucia)

Distributing Computation across Devices

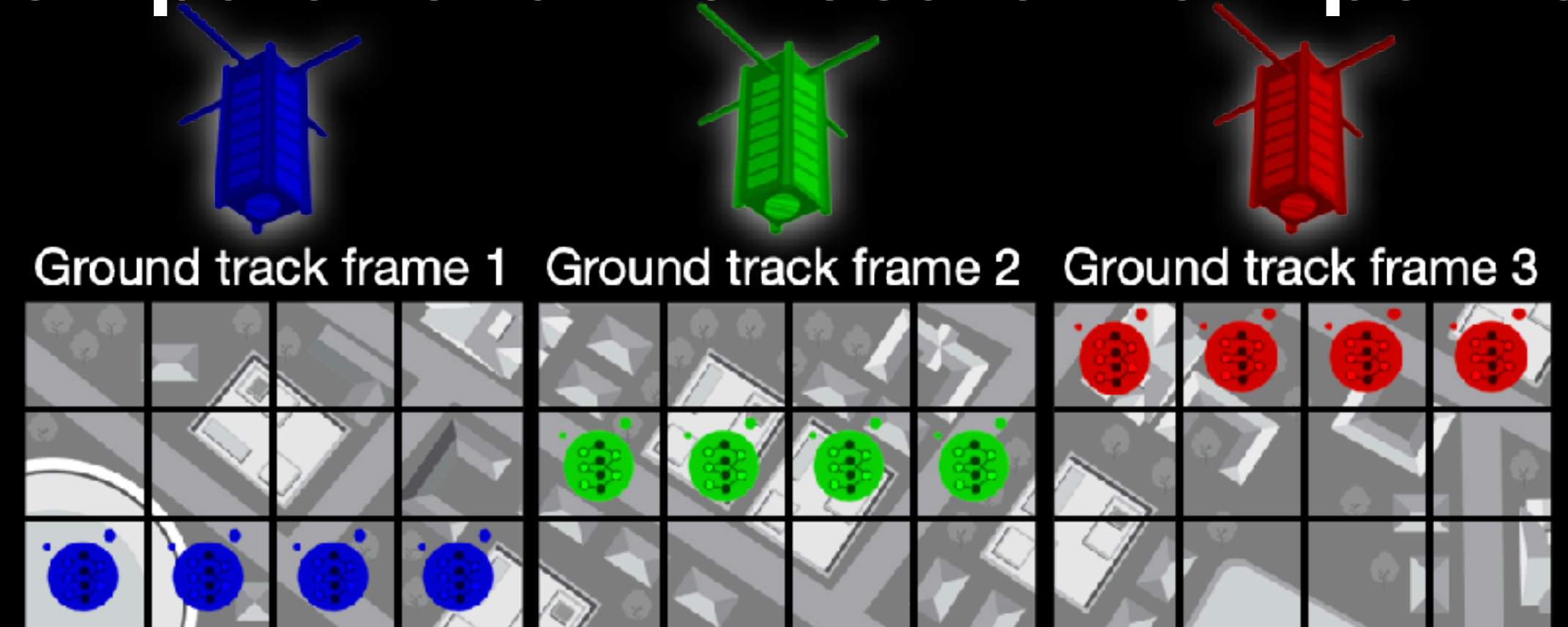
Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System (ASPLOS'20; B Denby, B Lucia)

Computational Nanosatellites

Machine Learning in Space



Computational Nanosatellite Pipelines



Machine Learning Bridges the Gap

Orbital Edge Computing: Machine Inference in Space
(CAL'19; B Denby, B Lucia)

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Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System (ASPLOS'20; B Denby, B Lucia)

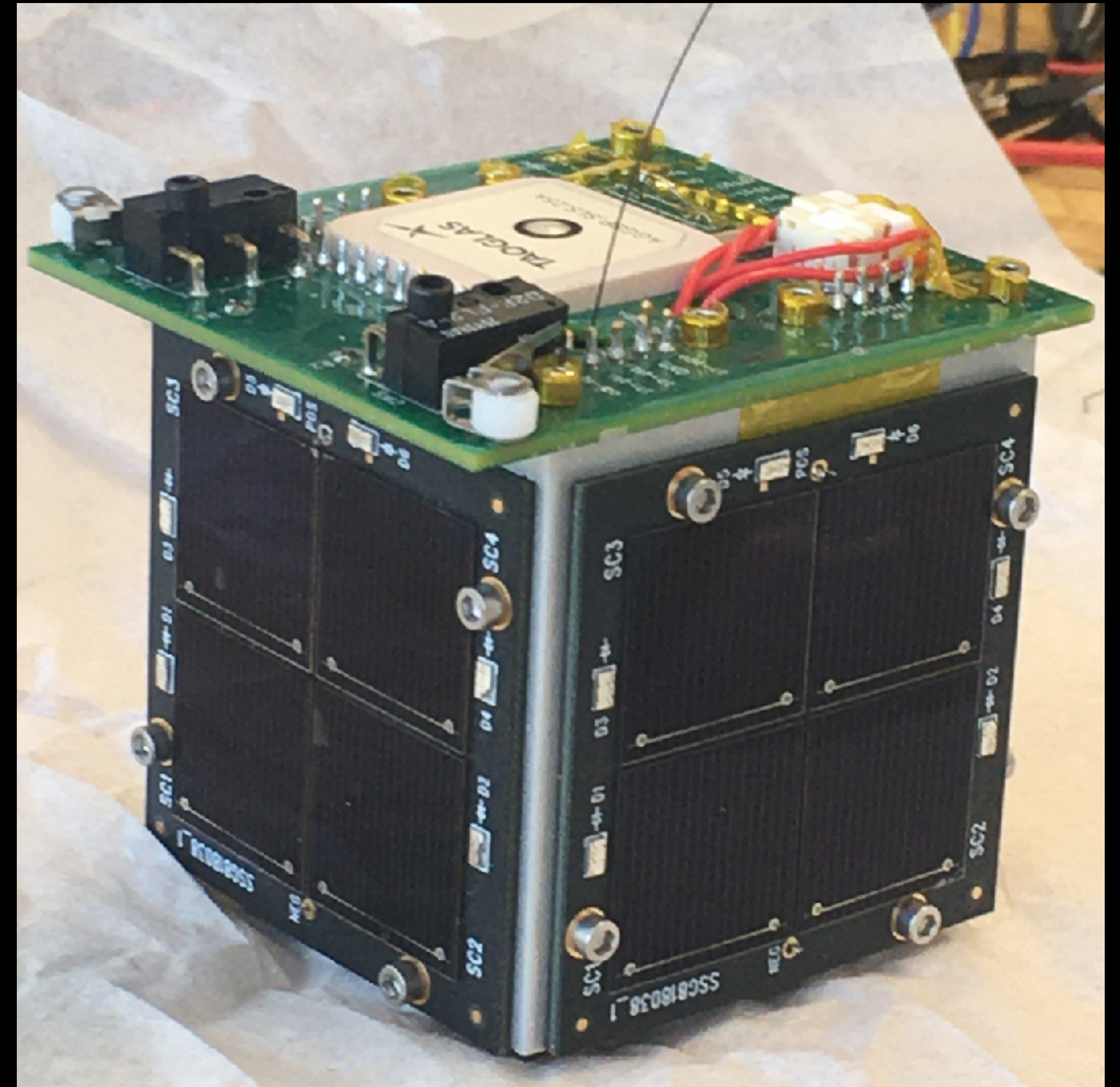
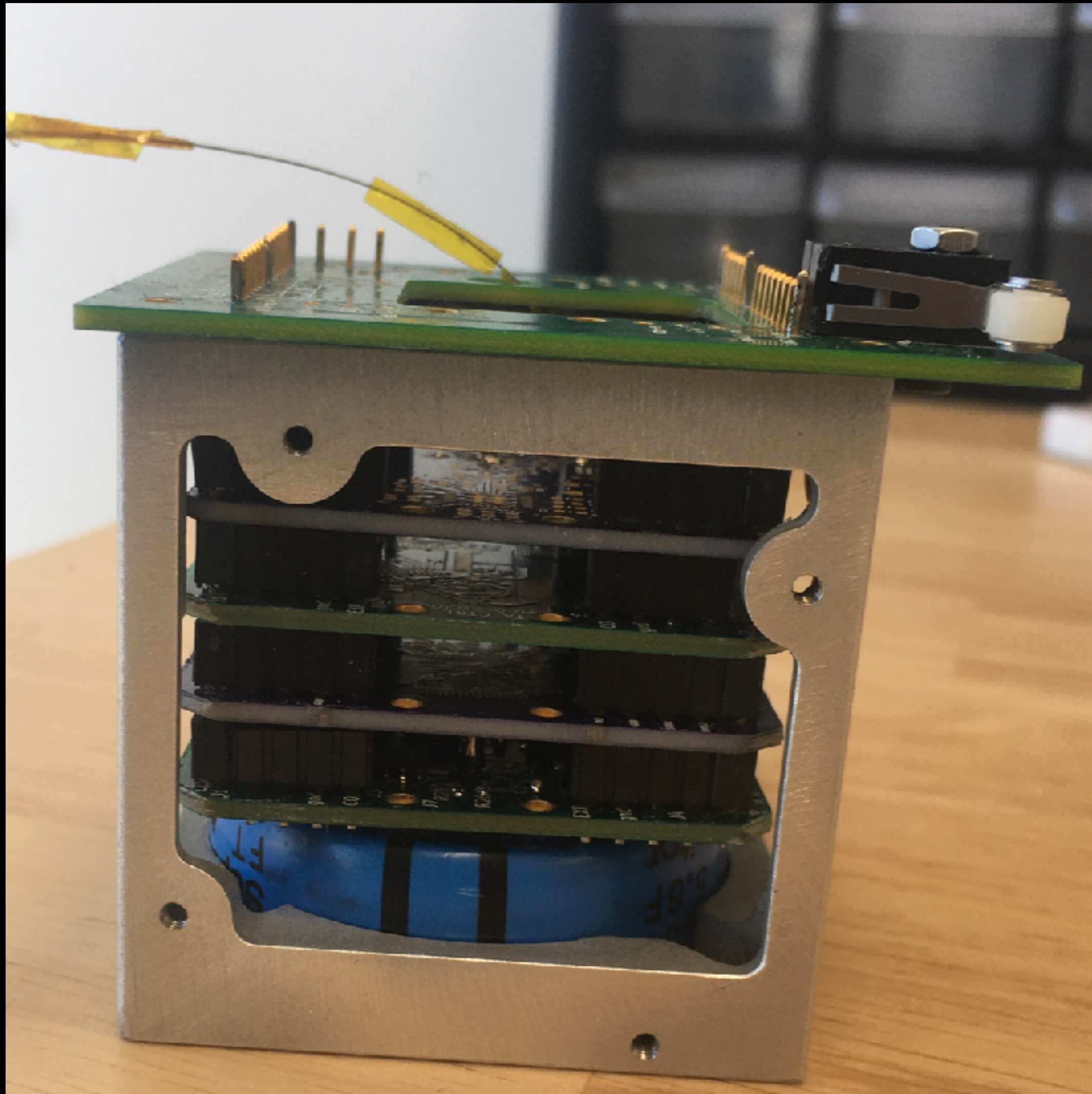
Emerging Challenges for Computational Nanosatellites



Computational Nanosatellite Constellations: Opportunities and Challenges
(GetMobile'21; B Lucia, B Denby, Z Manchester, H Desai, E Ruppel, A Colin)

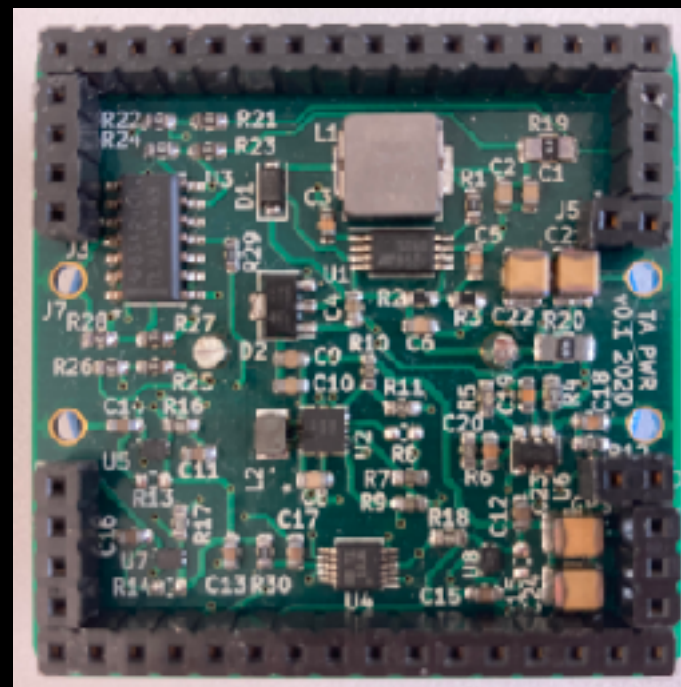
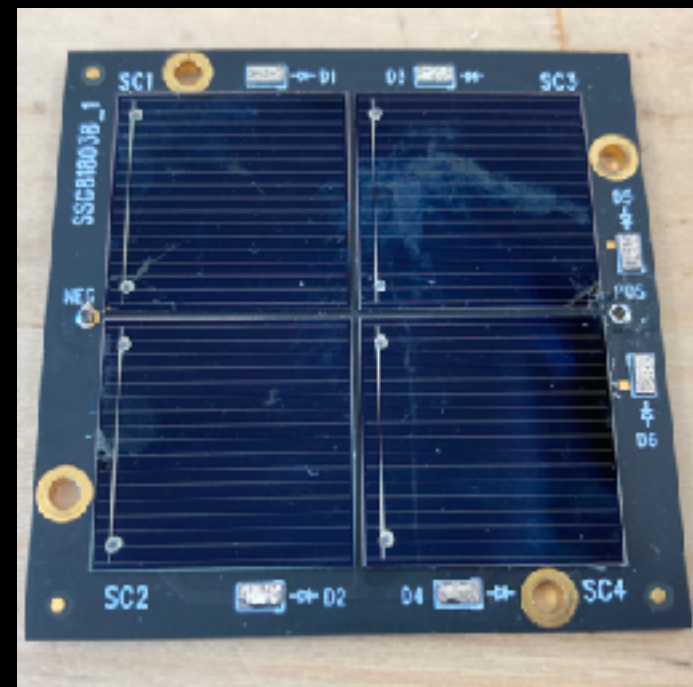
Tartan Artibeus: Evaluation in Space

5 cm

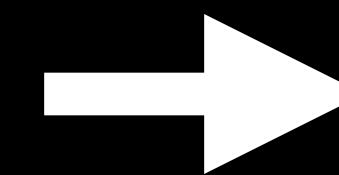
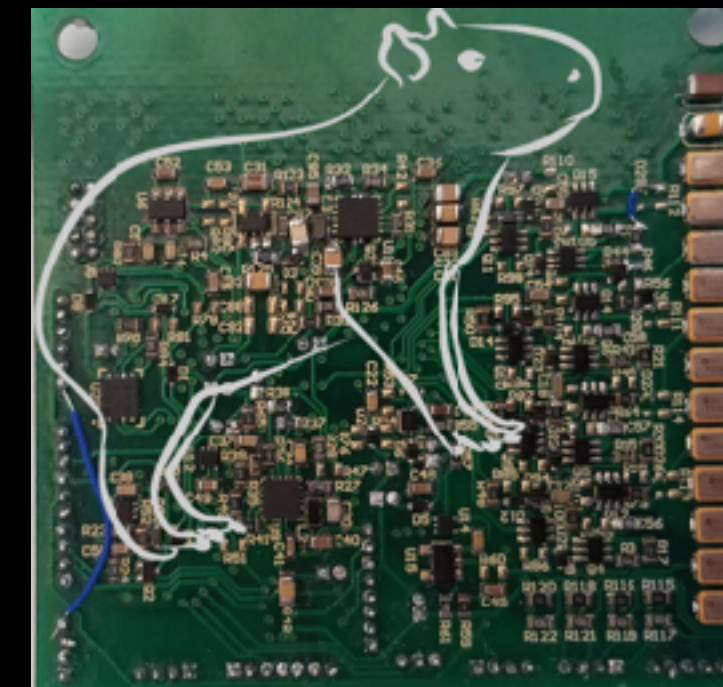


Tartan Artibeus: Evaluation in Space

Energy System



Command and Control

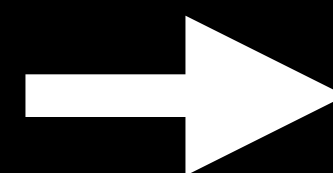
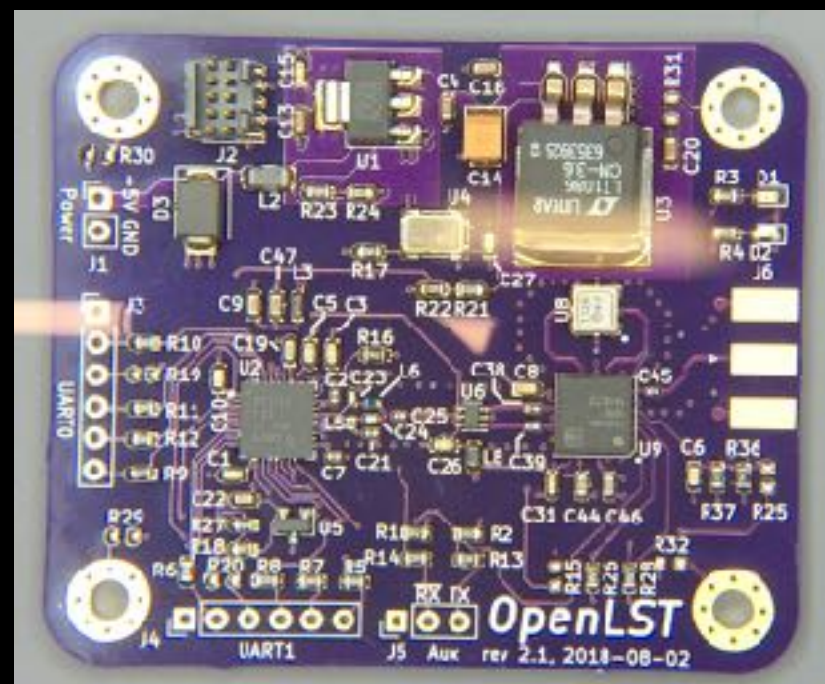


Capybara

Pocketcube C&DH

*Tartan Artibeus: A Batteryless, Computational Satellite Research Platform
(SmallSat'22; B Denby, E Ruppel, V Singh, S Che, C Taylor, F Zaidi, S Kumar, Z Manchester, B Lucia)*

Radio Communication



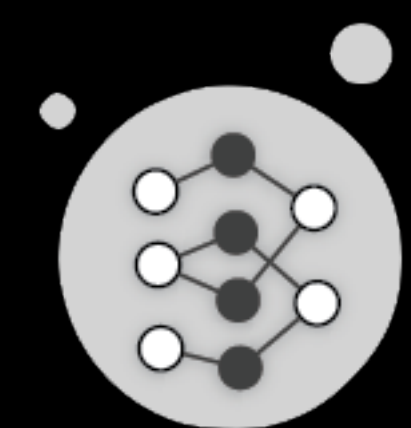
OpenLST

Pocketcube Radio

Computational Payload



cote



<https://github.com/cmuabstract/tartan-artibeus-hw>

Overview

Background and Related Work

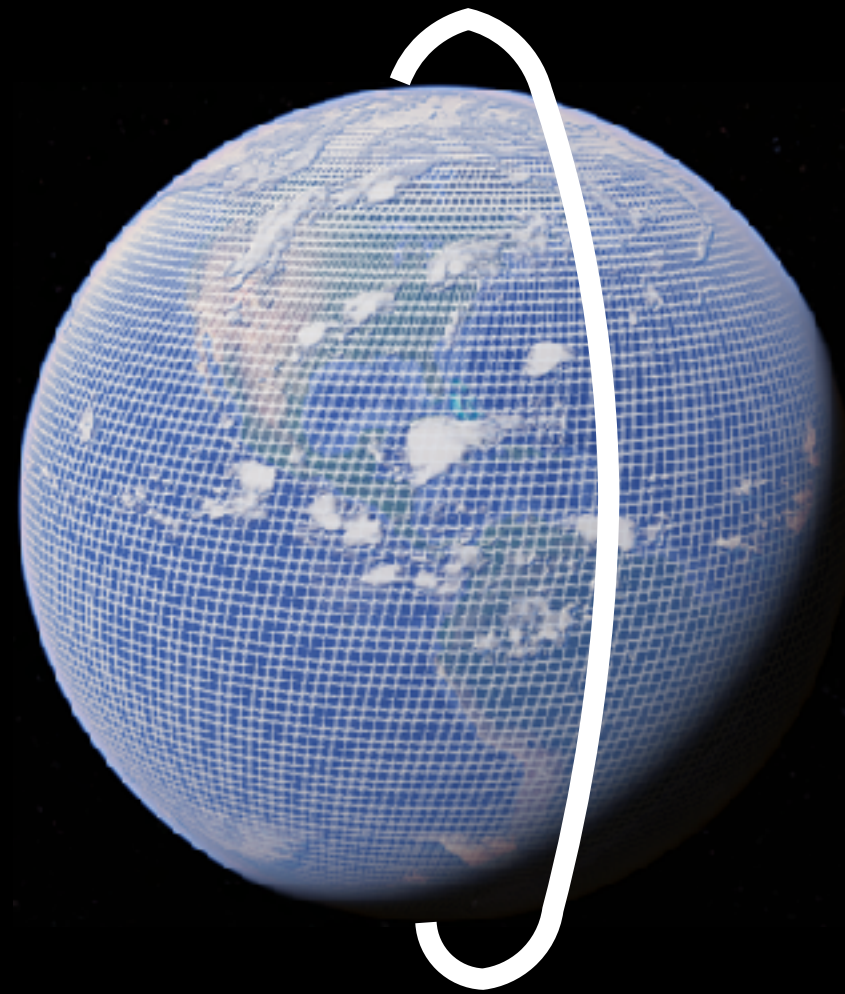
Components of Space Simulation

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Components of Space Simulation

Orbital Mechanics



Orbital Mechanics

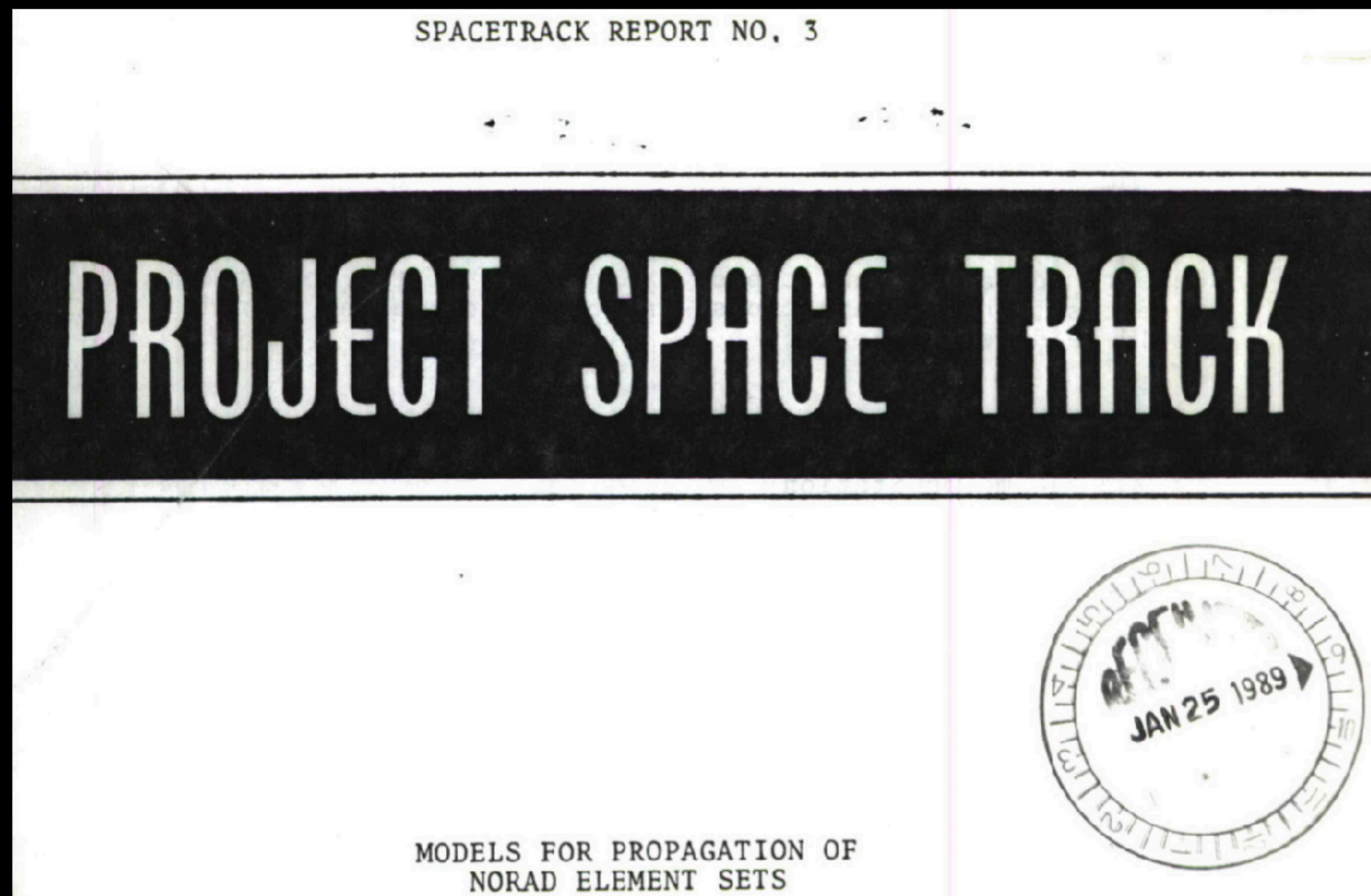
SPACETRACK REPORT NO. 3

PROJECT SPACE TRACK

MODELS FOR PROPAGATION OF
NORAD ELEMENT SETS



Orbital Mechanics



- SGP4: Simplified General Perturbations 4
 - Input: Date, Time, and Satellite TLE (two-line element set)
 - Output: Three-dimensional satellite position
- Benefits: Calculate the position of any publically-deployed satellite
- Drawbacks: Limited utility for modeling the position of prospective satellites

SGP4 Implementation in cote

6 THE SGP4 MODEL

The NORAD mean element sets can be used for prediction with SGP4. All symbols not defined below are defined in the list of symbols in Section Twelve. The original mean motion (n_0^*) and semimajor axis (a_0^*) are first recovered from the input elements by the equations

$$\begin{aligned}a_1 &= \left(\frac{a_0}{a_{10}}\right)^{\frac{3}{2}} \\ \delta_1 &= \frac{3}{2} \frac{k_2}{a_0^2} \frac{(3 \cos^2 i_0 - 1)}{(1 - e_0^2)^{\frac{3}{2}}} \\ a_0 &= a_1 \left(1 - \frac{1}{3} i_0 - i_0^2 - \frac{134}{81} i_0^3\right) \\ \delta_0 &= \frac{3}{2} \frac{k_2}{a_0^2} \frac{(3 \cos^2 i_0 - 1)}{(1 - e_0^2)^{\frac{3}{2}}} \\ n_0^* &= \frac{n_0}{1 + \delta_0} \\ a_0^* &= \frac{a_0}{1 - \delta_0}\end{aligned}$$

For perigee between 98 kilometers and 136 kilometers, the value of the constant s used in SGP4 is changed to

$$s^* = a_0^*(1 - e_*) = s + a_0$$

For perigee below 98 kilometers, the value of s is changed to

$$s^* = 20/\text{XKMPPER} + e_0$$

If the value of s is changed, then the value of $(a_0 - s)^{\frac{3}{2}}$ must be replaced by

$$(a_0 - s^*)^{\frac{3}{2}} = \left[[(a_0 - s)^{\frac{3}{2}}] + s - s^*\right]^{\frac{2}{3}}$$

Then calculate the constants (using the appropriate values of s and $(a_0 - s)^{\frac{3}{2}}$)

$$\theta = \cos i_0$$

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$$\frac{3k_2 n_0^* a_0^* \sin i_0}{a_0^* s}$$

$$C_4 = -2n_0^*(a_0 - s)^{\frac{3}{2}} \zeta^2 a_0^* \delta_1^{\frac{3}{2}} (1 - \eta^2)^{-\frac{3}{2}} \left[\left(2i_0(1 + e_0) + \frac{1}{2} i_0^2 + \frac{1}{2} i_0^3 \right) - \frac{2k_2 f}{a_0^*(1 - \eta^2)} \eta \right. \\ \left. \left[\left(\frac{3}{2} + \frac{3}{2} \theta^2 \right) \left(1 + \frac{3}{2} \eta^2 \right) - 2e_0 \eta + \frac{1}{2} e_0^2 \eta^2 \right] + \frac{3}{4} (1 - \theta^2) (2\eta^2 - e_0 \eta - e_0^2 \eta^2) \cos 2\omega_0 \right]$$

$$C_5 = 2(a_0 - s)^{\frac{3}{2}} \zeta^2 a_0^* \delta_0^2 (1 - \eta^2)^{-\frac{3}{2}} \left[1 + \frac{11}{4} \eta (\eta + e_0) + e_0 \eta^2 \right]$$

$$D_2 = 4e_0^2 \zeta C_3^2$$

$$D_3 = \frac{4}{3} a_0^* \zeta^2 (7a_0^* + s) C_1^2$$

$$D_4 = \frac{2}{3} a_0^* \zeta^2 (221a_0^* + 31s) C_1^4$$

The secular effects of atmospheric drag and gravitation are isolated through the equations

$$M_{D,N} = M_2 \cdot \left[1 + \frac{3k_2(-1 + 2\theta^2)}{2a_0^* \delta_0^2} + \frac{3k_2^2(13 - 76\theta^2 + 157\theta^4)}{15a_0^* \delta_0^4} \right] a_0^*(t - t_0)$$

$$\omega_{D,N} = \omega_0 + \left[-\frac{3k_2(1 - 3\theta^2)}{2a_0^* \delta_0^2} + \frac{3k_2^2(7 - 112\theta^2 + 205\theta^4)}{15a_0^* \delta_0^4} - \frac{3k_2(3 - 36\theta^2 + 199\theta^4)}{4a_0^* \delta_0^2} \right] a_0^*(t - t_0)$$

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$$\Omega_{D,N} = \Omega_0 + \left[-\frac{3k_2\theta}{a_0^* \delta_0^2} + \frac{3k_2^2(4\theta - 19\theta^2)}{2a_0^* \delta_0^4} + \frac{3k_2\theta(3 - 7\theta^2)}{2a_0^* \delta_0^2} \right] a_0^*(t - t_0)$$

$$\delta\omega = B^* C_2 (\cos i_0) (t - t_0)$$

$$\delta M = -\frac{2}{3} (a_0 - s)^{\frac{3}{2}} B^* \zeta^2 \frac{a_0^*}{e_0 \eta} [(1 + \eta \cos M_{D,N})^3 - (1 + \eta \cos M_0)^3]$$

$$M_p = M_{D,N} + \delta\omega + \delta M$$

$$\omega = \omega_{D,N} + \delta\omega + \delta M$$

$$\Omega = \Omega_{D,N} - \frac{21}{2} \frac{a_0^* \eta_0 \theta}{a_0^* \delta_0^2} C_1 (t - t_0)^2$$

$$e = e_0 + B^* C_4 (t - t_0) + B^* C_2 (\sin M_p - \sin M_0)$$

$$u = a_0^* [1 - C_3(t - t_0) - D_2(t - t_0)^2 - D_3(t - t_0)^3 - D_4(t - t_0)^4]$$

$$E = M_p + \omega + \Omega + n_0^* \left[\frac{3}{2} C_1 (t - t_0)^2 + (D_1 + 2C_1^2) (t - t_0)^3 \right. \\ \left. + \frac{1}{2} (2D_2 + 12C_1 D_2 + 12C_1^2 D_2 + 16C_1^3) (t - t_0)^4 \right. \\ \left. + 12C_1 D_3 + 6D_2^2 + 30C_1^2 D_2 + 16C_1^3) (t - t_0)^5 \right]$$

12

use epoch. It should be noted that when epoch perigee height is less than 100 kilometers, a and E are truncated after the C_3 term, and the terms involving a^2 are

and periodic terms

with

$$\Delta(E + \omega)_1 = \frac{U - e_{2,N} \cos(E + \omega)_1 + a_{2,N} \sin(E + \omega)_1 - (E + \omega)_1}{a_{2,N} \sin(E + \omega)_1 - a_{2,N} \cos(E + \omega)_1 + 1}$$

and

$$(E + \omega)_2 = U$$

The following equations are used to calculate preliminary quantities needed for short-period periods

$$e \cos E = e_{2,N} \cos(E + \omega) + a_{2,N} \sin(E + \omega)$$

$$e \sin E = a_{2,N} \sin(E + \omega) - e_{2,N} \cos(E + \omega)$$

$$u_0 = (a_{2,N}^2 + a_{2,N}^2)^{\frac{1}{2}}$$

$$p_0 = a_0^* (1 - e_0^2)$$

$$r = a_0^* (1 - e \cos E)$$

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$$\dot{r} = h_0 \frac{\sqrt{a}}{r} \cos \Delta$$

$$r \dot{f} = h_0 \frac{\sqrt{p_0}}{r}$$

$$\cos \alpha = \frac{a}{r} \left[\cos(E + \omega) - a_{2,N} + \frac{a_{2,N}(\sin E)}{1 + \sqrt{1 - e_{2,N}^2}} \right]$$

$$\sin \alpha = \frac{a}{r} \left[\sin(E + \omega) - a_{2,N} - \frac{a_{2,N}(\cos E)}{1 + \sqrt{1 - e_{2,N}^2}} \right]$$

$$\alpha = \tan^{-1} \left(\frac{\sin \alpha}{\cos \alpha} \right)$$

$$\Delta r = \frac{h_2}{2a_0^*} (1 - \theta^2) \cos 2\alpha$$

$$\Delta \alpha = -\frac{h_2}{2a_0^*} (7\theta^2 - 1) \sin 2\alpha$$

$$\Delta \Omega = \frac{3k_2 \theta}{2a_0^* \delta_0^2} \sin 2\omega$$

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$$\theta^2 \sin 2\alpha$$

$$\theta^2 \cos 2\alpha - \frac{3}{2} (1 - \theta^2)$$

corrections are added to give the osculating quantities

$$\frac{1 - e_{2,N}}{a_0^*} (2\theta^2 - 1) + \Delta r$$

15

vectors are calculated by

$$\dot{r} = \dot{r} \cos \alpha$$

$$\dot{\alpha} = \dot{\alpha} \sin \alpha$$

where

$$\mathbf{M} = \begin{bmatrix} M_x = -\sin i_0 \cos i_0 \\ M_y = \cos \Omega_0 \cos i_0 \\ M_z = \sin i_0 \end{bmatrix}$$

$$\mathbf{N} = \begin{bmatrix} N_x = -\cos \Omega_0 \\ N_y = \sin \Omega_0 \\ N_z = 0 \end{bmatrix}$$

Then position and velocity are given by

$$\mathbf{r} = r_1 \mathbf{U}$$

and

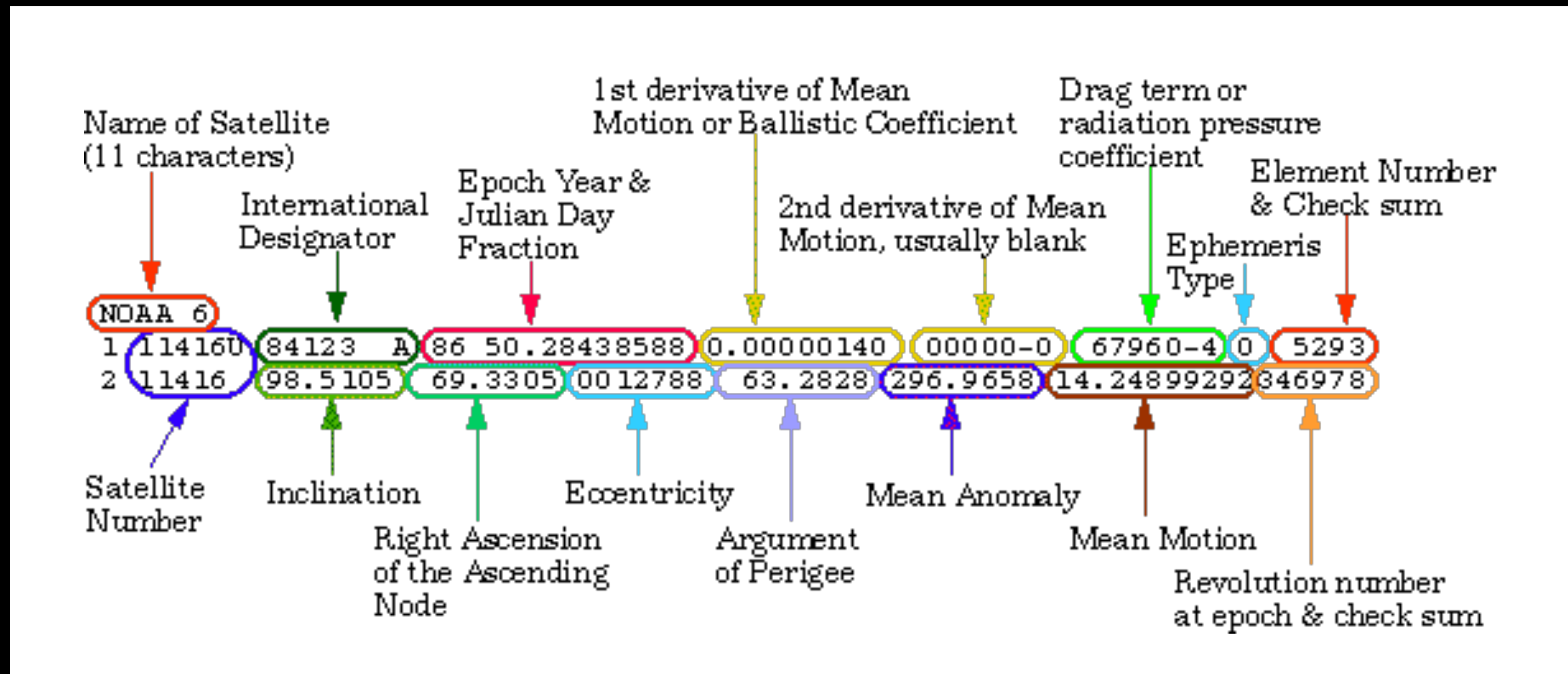
$$\dot{\mathbf{r}} = r_1 \mathbf{U} + (\dot{r} \dot{f})_1 \mathbf{V}$$

A FORTRAN IV computer code listing of the subroutine SGP4 is given below. These equations contain all currently anticipated changes to the SGP4 operational program. These changes are scheduled for implementation in March, 1981.

16

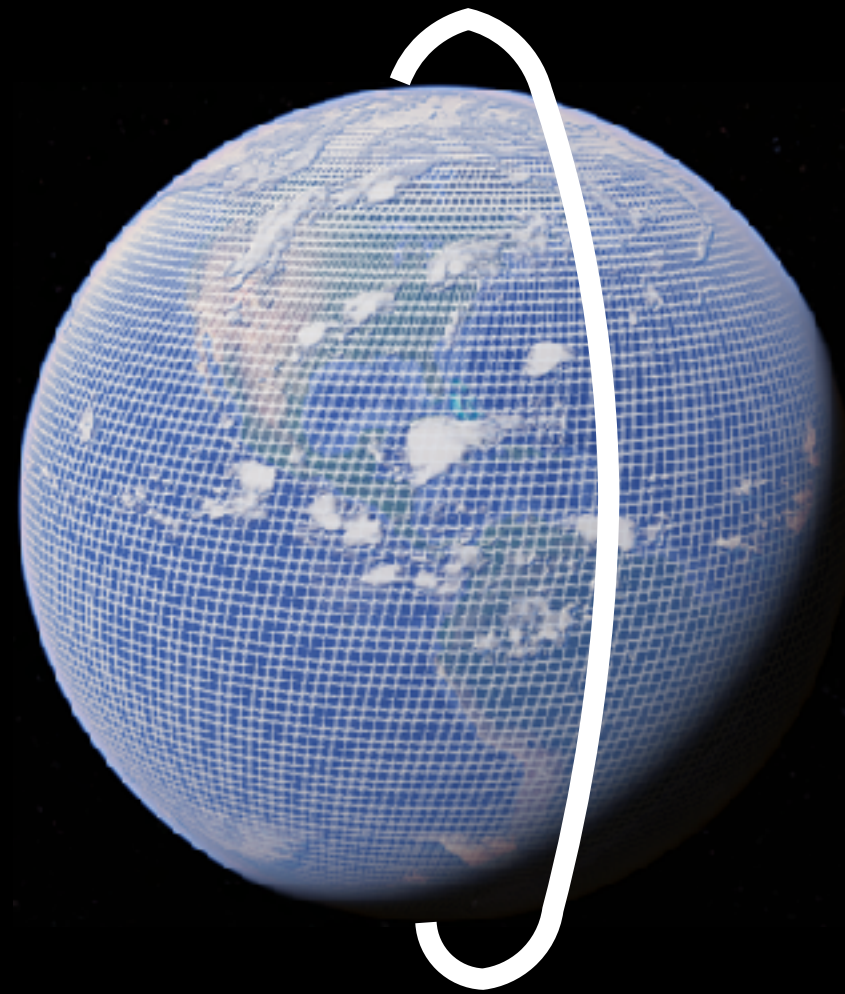
SGP4 Input: TLE (Two-line element set)

TLEs for all satellites are posted ~daily for download

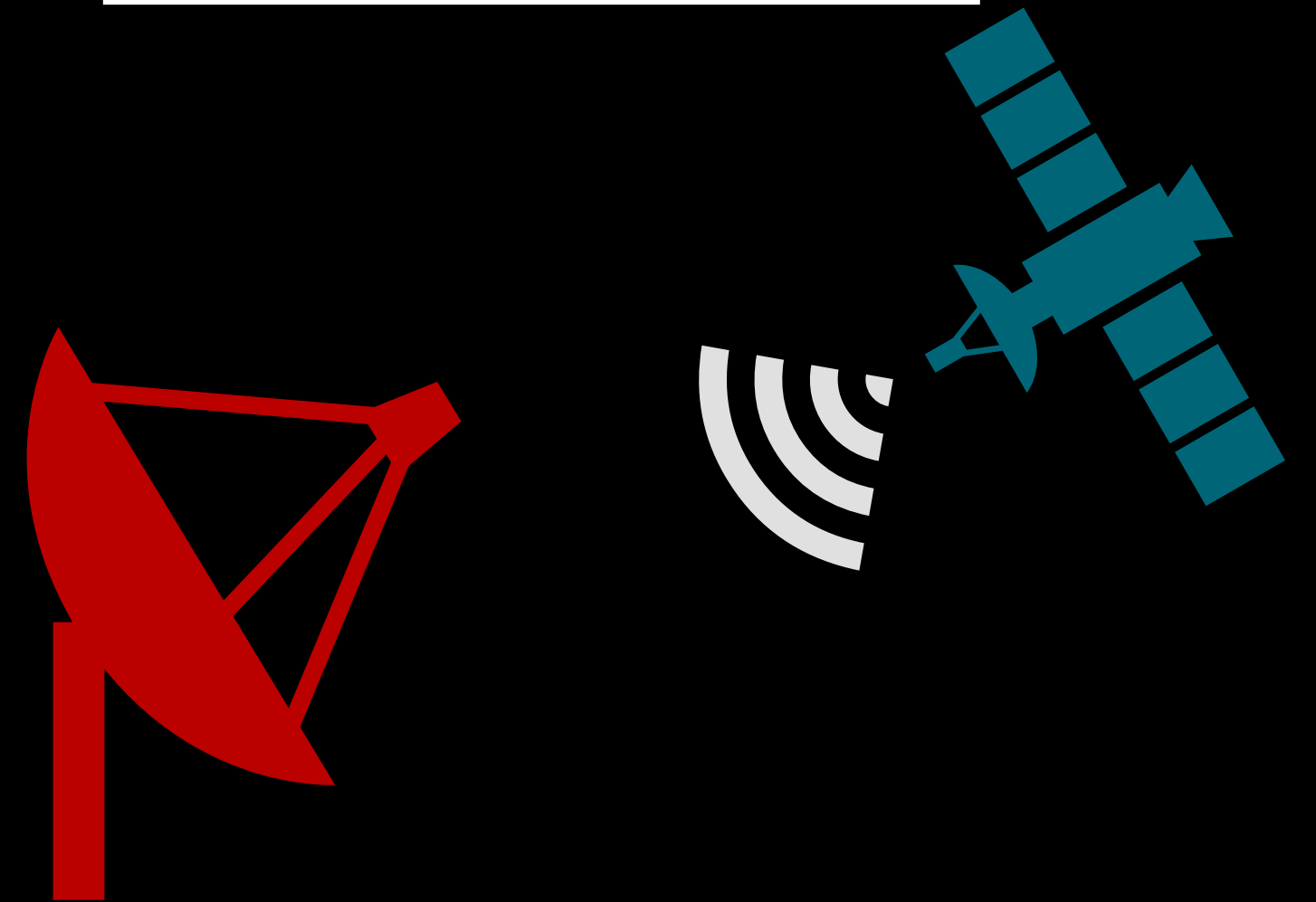


Components of Space Simulation

Orbital Mechanics



Communication



Satellite Communications

Space Mission Analysis and Design Third Edition

Edited by

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United States Air Force Academy

and

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Douglas Kirkpatrick, United States Air Force Academy
Donna Klungle, Microcosm, Inc.

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Chapter 13

Communications Architecture

Fred J. Dietrich, Globalstar L.P.
Richard S. Davies, Stanford Telecommunications, Inc.

- 13.1 Communications Architecture
Communications Architecture Defined by Satellite-Ground Station Geometry; Communications Architecture Defined by Function; Criteria for Selecting Communications Architecture
- 13.2 Data Rates
TT&C; Data Collection; Data Relay
- 13.3 Link Design
Derivation of Link Equation; Link Design Equations; Modulation and Coding; Atmospheric and Rain Attenuation; Frequency Selection; Link Budgets
- 13.4 Sizing the Communications Payload
- 13.5 Special Topics
Multiple Access; Sharing Communication Links; Payloads with Onboard Processing; Antijam Techniques; Security; Diversity Techniques; Optical Links

A *communications architecture* is the arrangement, or configuration, of satellites and ground stations in a space system, and the network of communication links that transfers information between them. This chapter discusses this arrangement of links, their operation, and their effect on system design. More detailed information on satellite communications is available in Morgan and Gordon [1989] and Sklar [1988].

Table 13-1 lists the steps required to specify the communications architecture. The first step is to define the mission objectives and requirements in enough detail to evaluate and compare alternative architectures. Section 13.1 describes alternative configurations and the criteria used in their selection.

Communication Modeling

Communication Modeling

Maximum communication bit rate:

$$R_{\max} = B \log_2(1 + C/N)$$

$R_{\max}$: channel bits/sec

B : channel bandwidth

C : received signal power

N : received noise power

Communication Modeling

Maximum communication bit rate:

$$R_{\max} = B \log_2(1 + C/N)$$

$R_{\max}$: channel bits/sec

B : channel bandwidth

C : received signal power

N : received noise power

Received signal power C :

$$C = PL_l G_t \left(\frac{\lambda}{4\pi S} \right)^2 L_a G_r$$

P : transmitted power

L_l : TX to ANT line loss factor

G_t : transmitter gain

λ : channel center freq. wavelength

S : separation vector magnitude

L_a : atmosphere loss factor

G_r : receiver gain

Communication Modeling

Maximum communication bit rate:

$$R_{\max} = B \log_2(1 + C/N)$$

$R_{\max}$: channel bits/sec

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N : received noise power

Received noise power N :

$$N = kT_s B$$

k : Boltzmann constant

T_s : receiver system noise temperature

B : channel bandwidth

Received signal power C :

$$C = PL_l G_t \left(\frac{\lambda}{4\pi S} \right)^2 L_a G_r$$

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P : transmitted power

L_l : TX to ANT line loss factor

G_t : transmitter gain

λ : channel center freq. wavelength

S : separation vector magnitude

L_a : atmosphere loss factor

G_r : receiver gain

Receiver system noise temperature T_s :

$$T_s = T_{\text{ant}} + \frac{1 - L_r}{L_r} T_0 + \frac{T_r}{L_r}$$

T_{ant} : RX antenna and environment factors

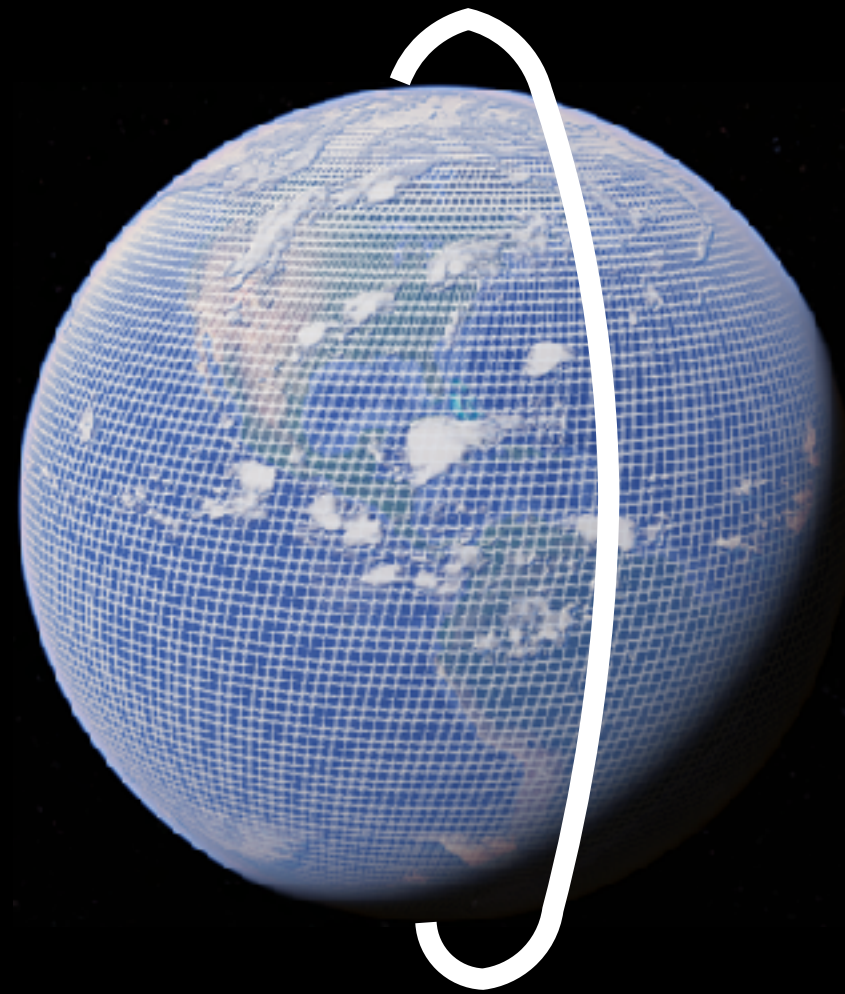
L_r : ANT to RX line loss

T_0 : 290 K

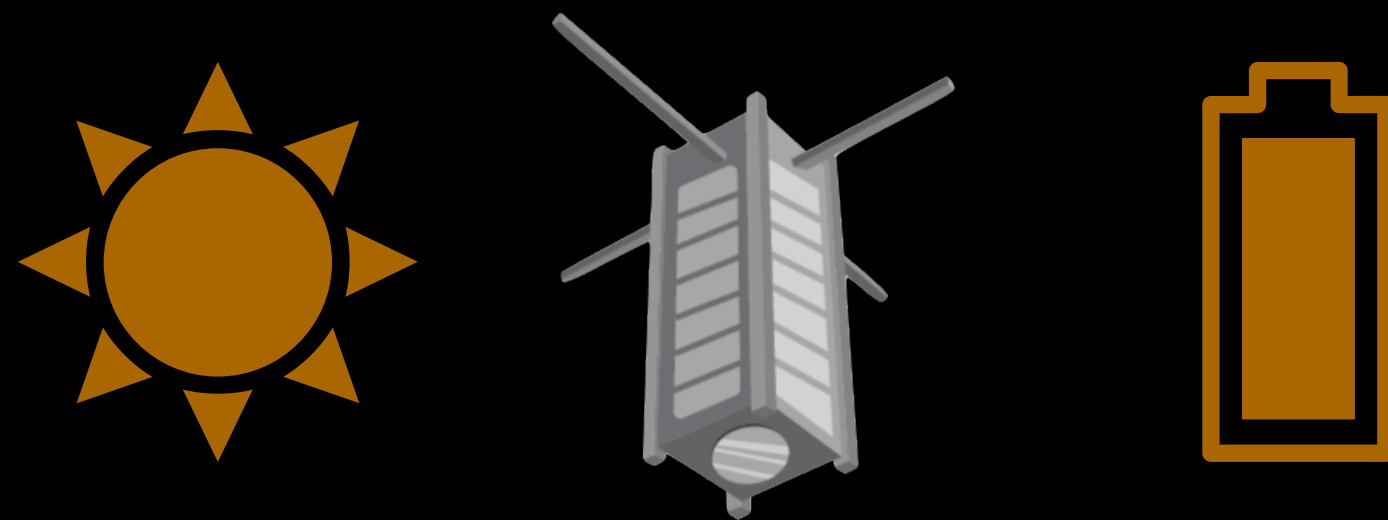
T_r : receiver noise temperature

Components of Space Simulation

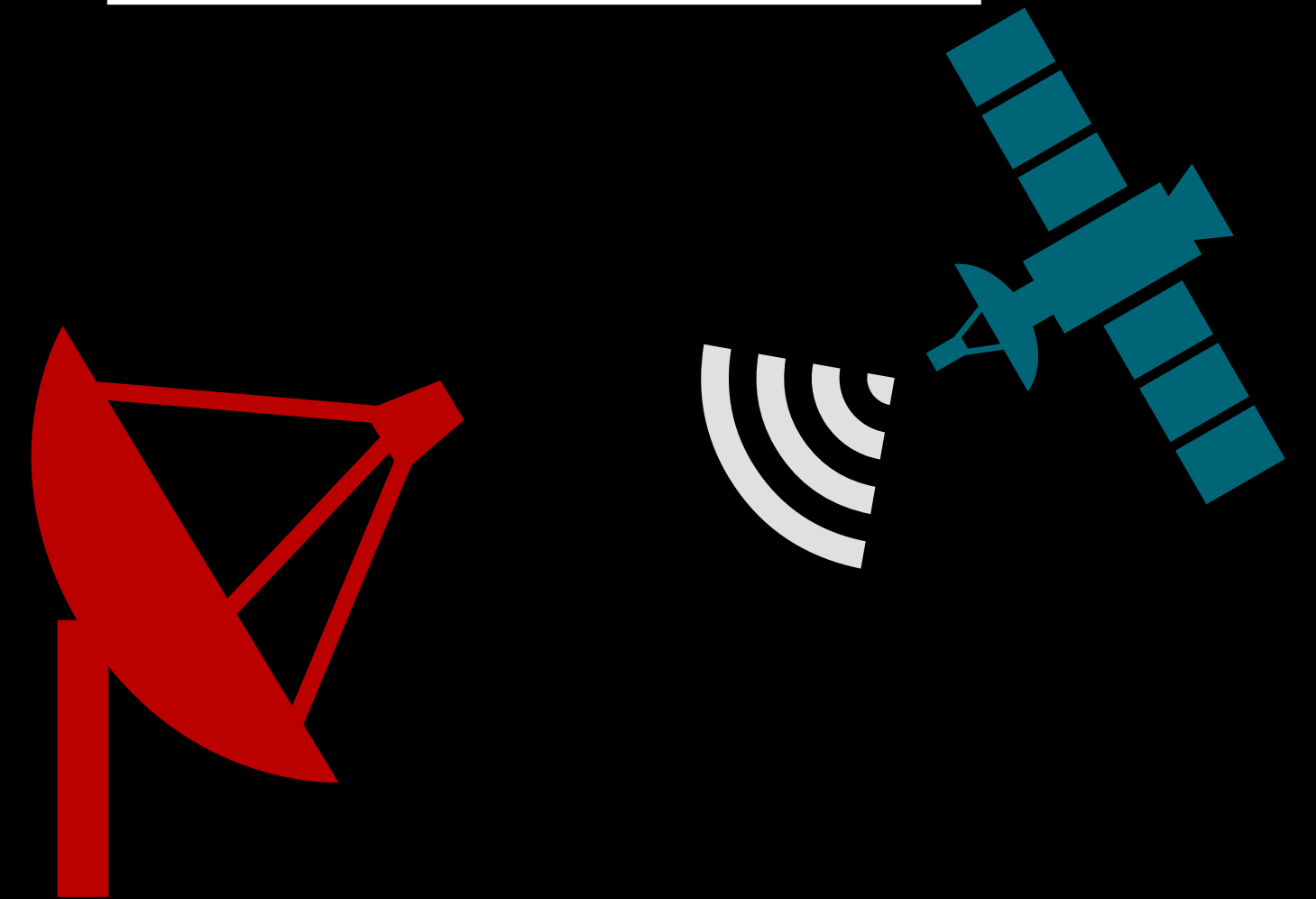
Orbital Mechanics



Energy and Power

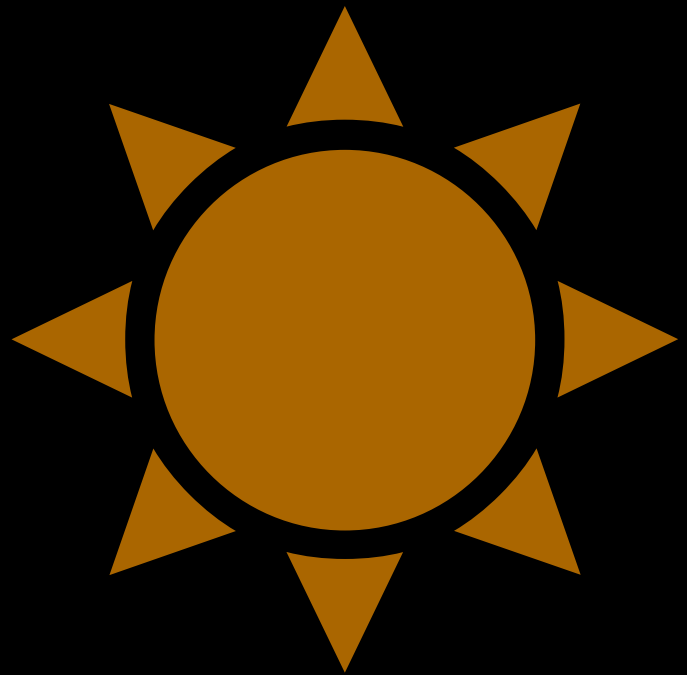


Communication



Satellite Energy Systems

Energy Source



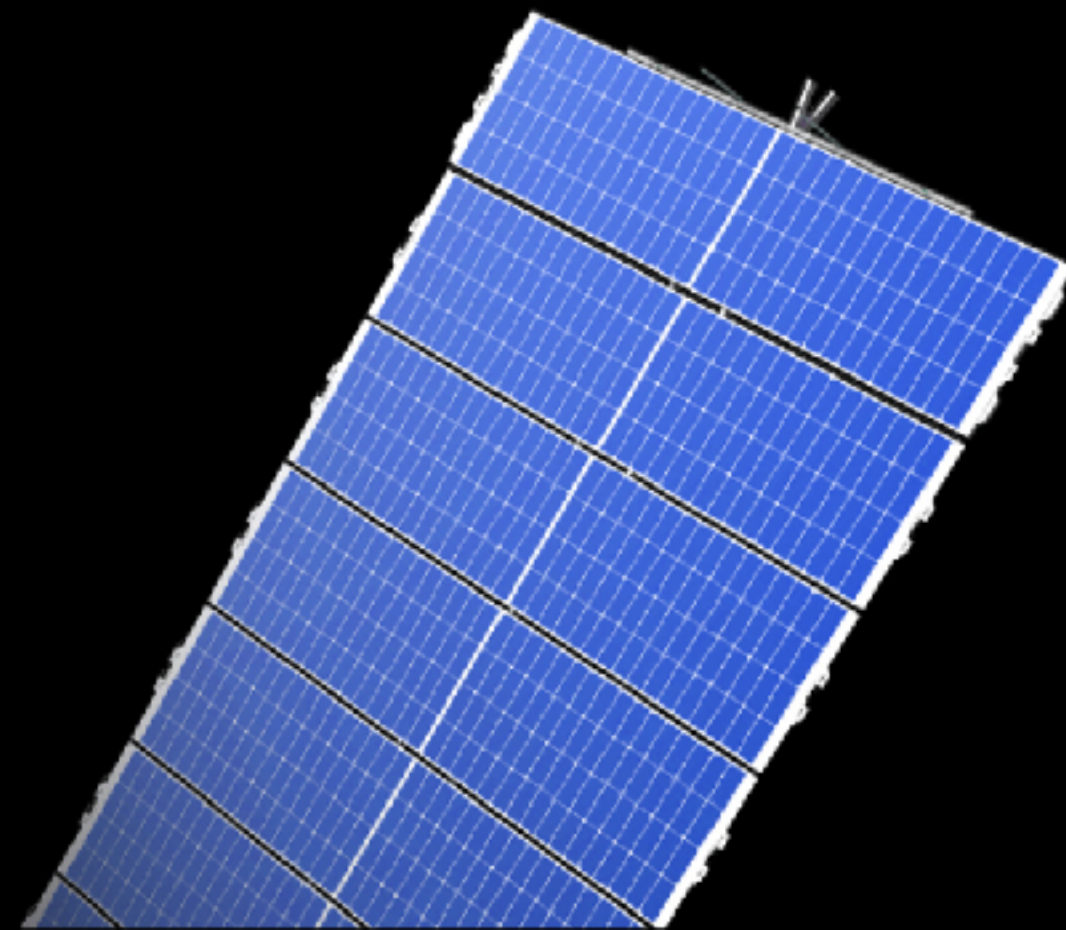
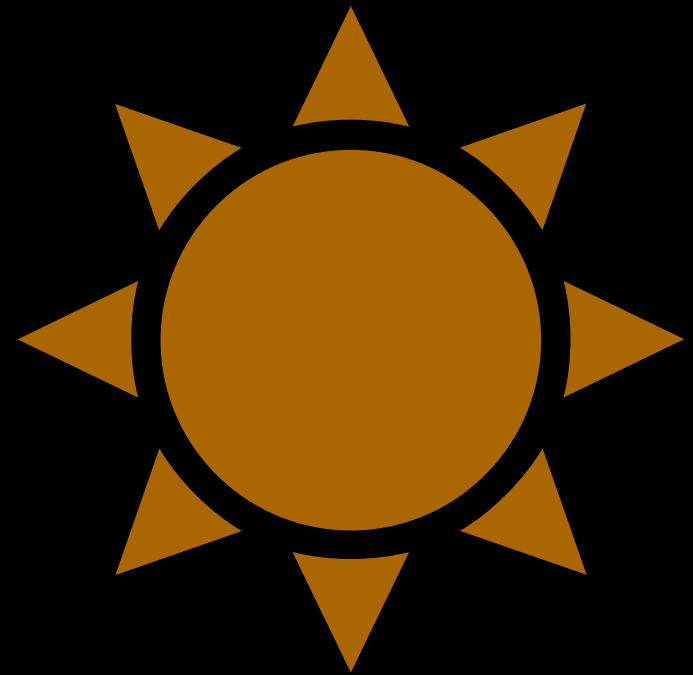
Irradiance

LEO: 1366 W/m²

Satellite Energy Systems

Energy Source

Energy Harvester

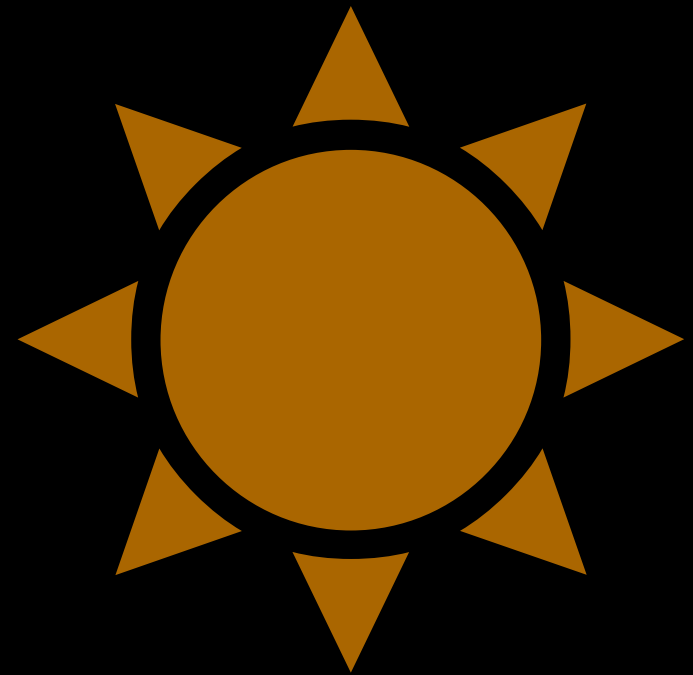


Irradiance
LEO: 1366 W/m²

Surface Area
Efficiency

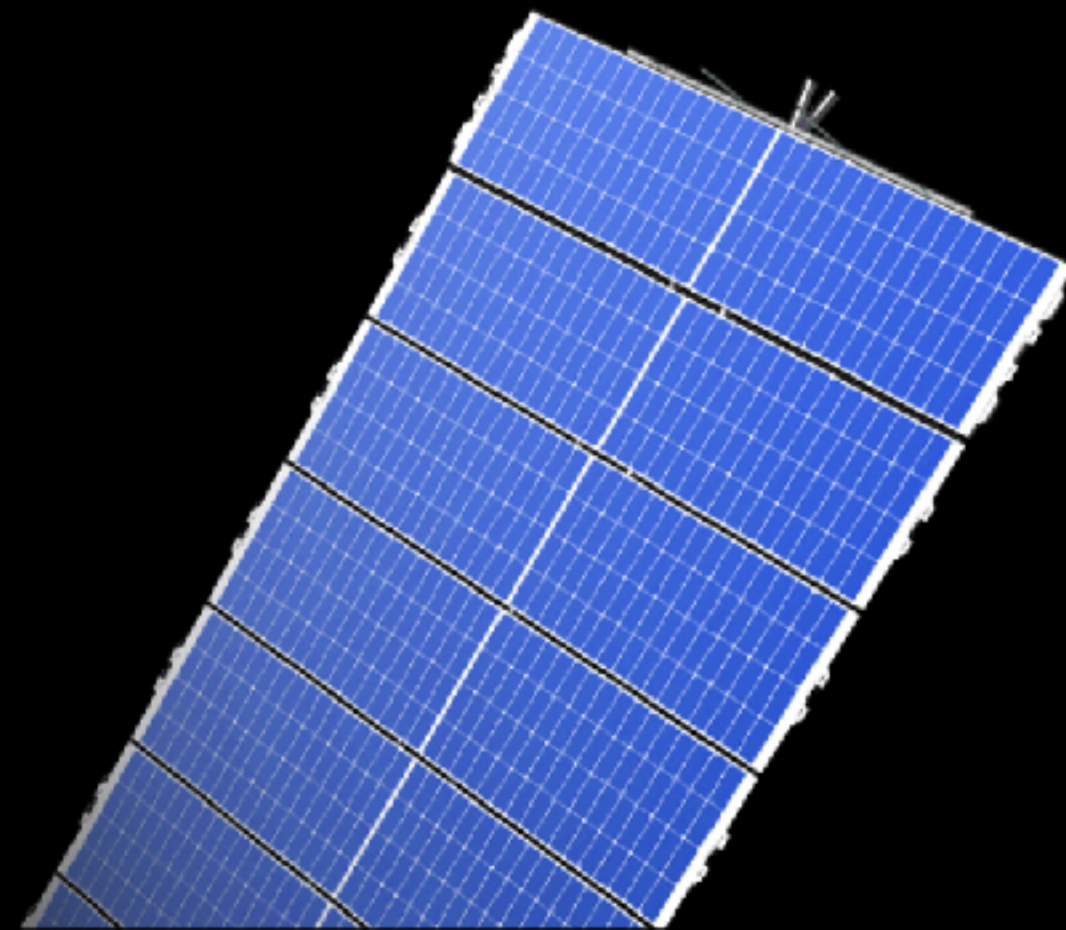
Satellite Energy Systems

Energy Source



Irradiance
LEO: 1366 W/m²

Energy Harvester



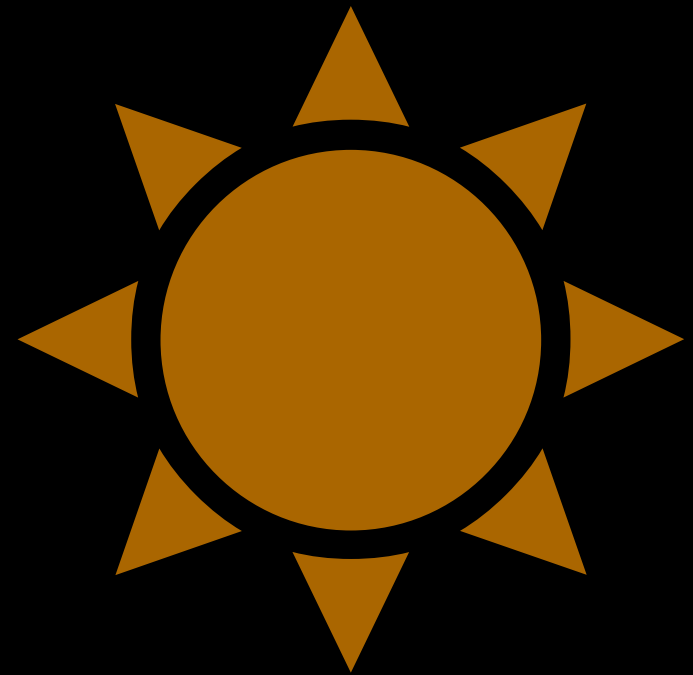
Surface Area
Efficiency

Energy Storage



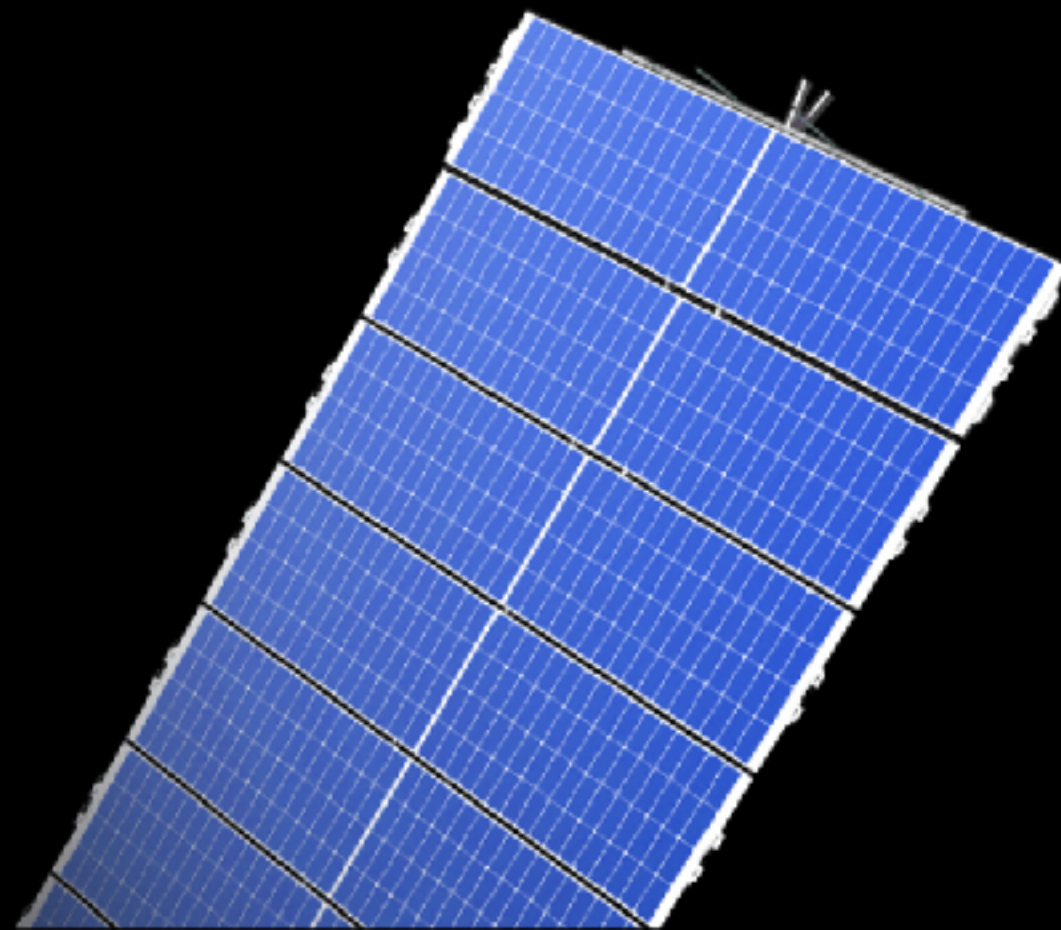
Satellite Energy Systems

Energy Source



Irradiance
LEO: 1366 W/m²

Energy Harvester

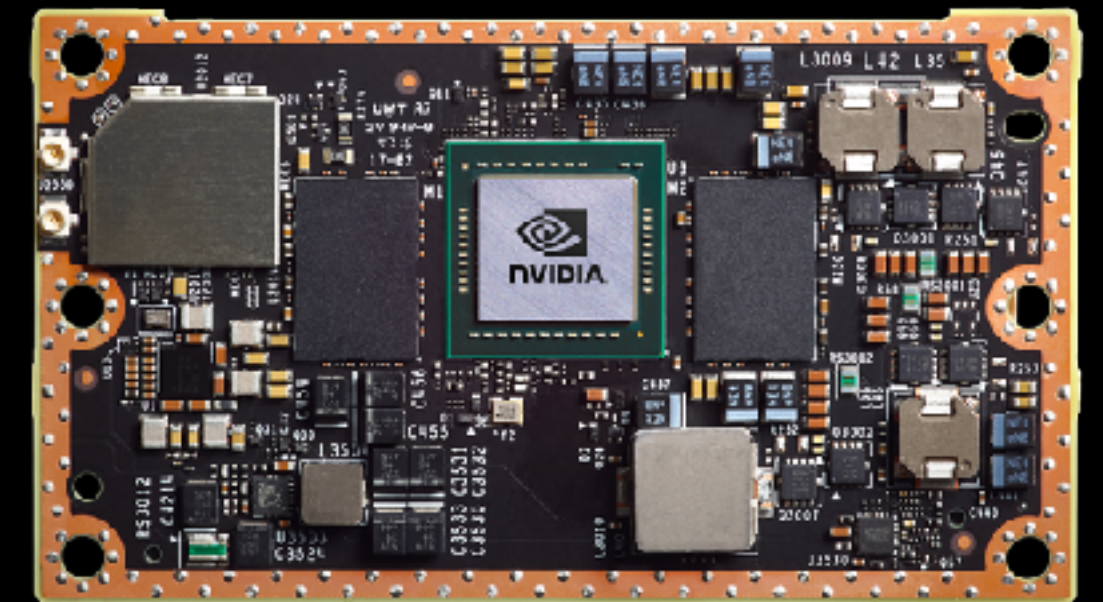


Surface Area
Efficiency

Energy Storage

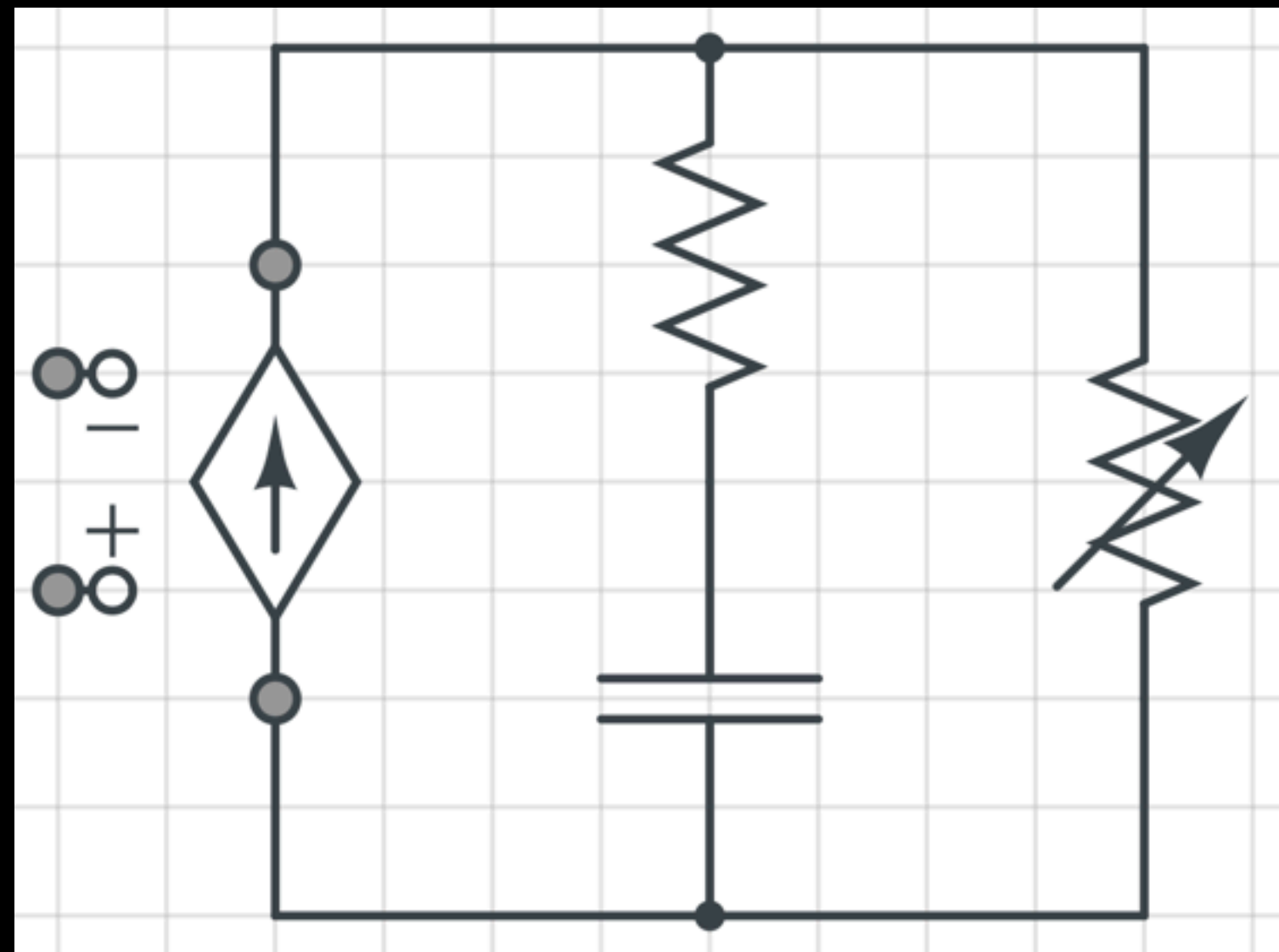


Energy Consumers



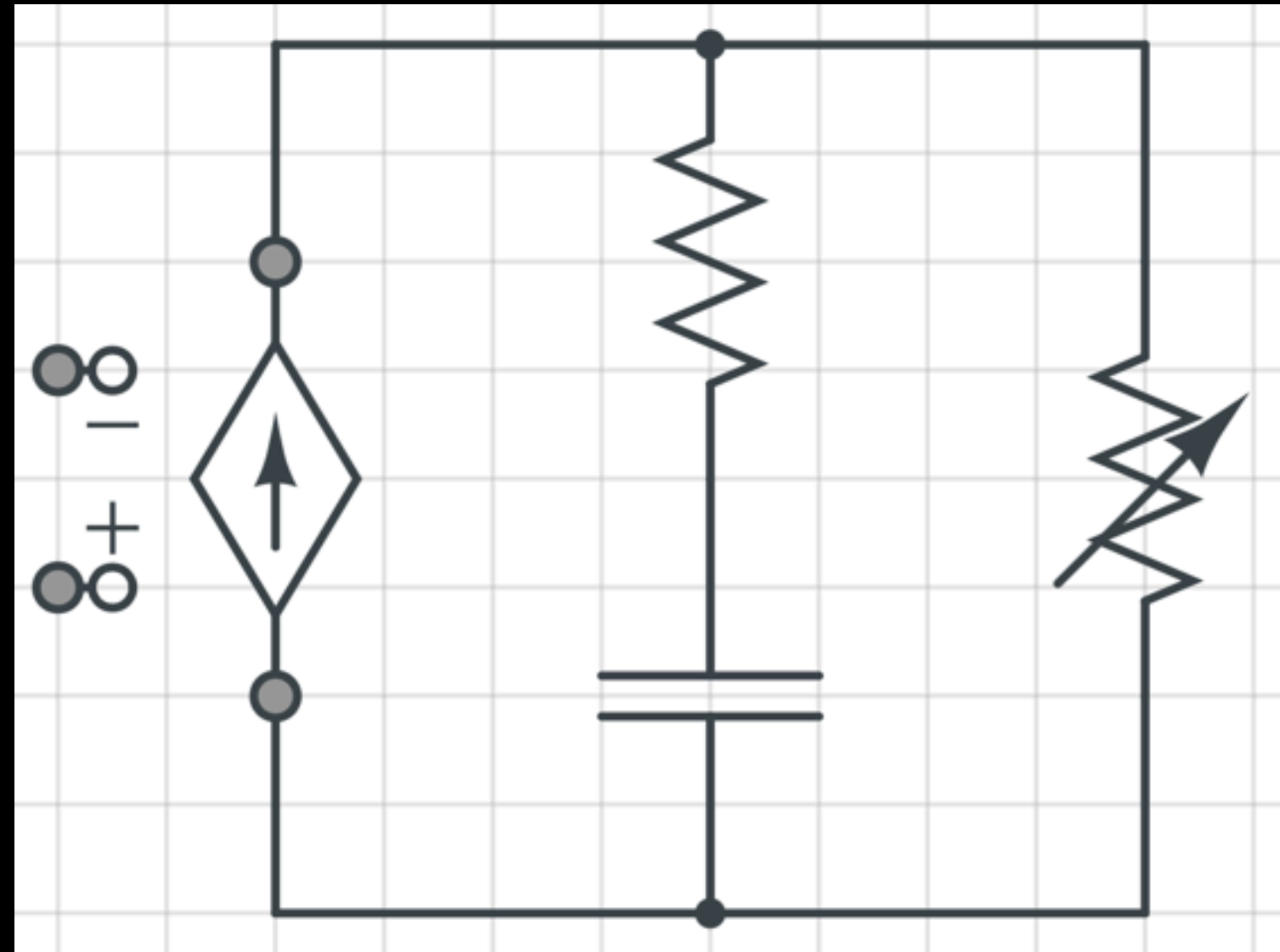
Energy Modeling

Energy Modeling



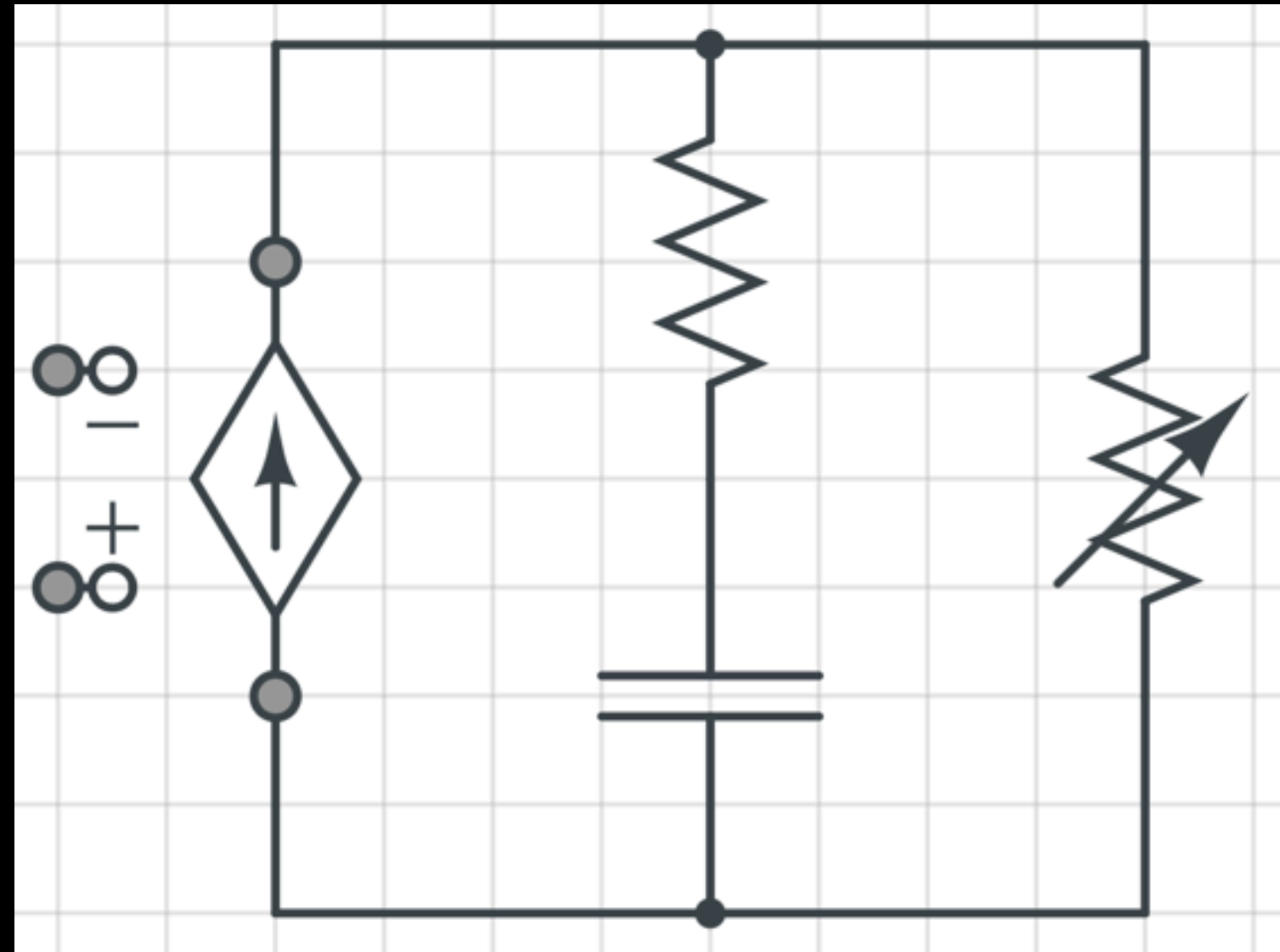
Energy Modeling

Energy harvester:
Solar cell



Energy Modeling

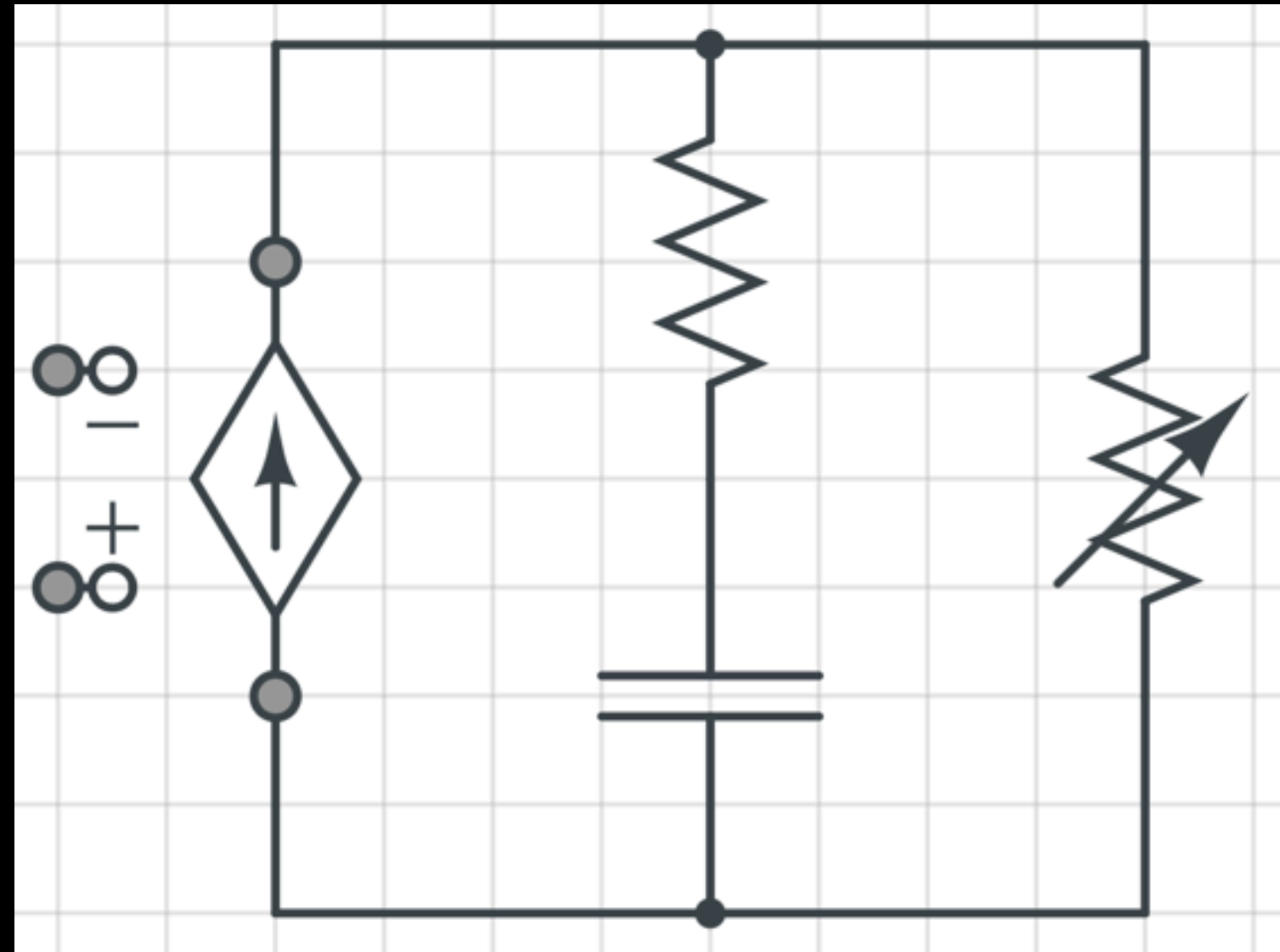
Energy harvester:
Solar cell



Energy storage:
Energy buffer with
Equivalent series resistance

Energy Modeling

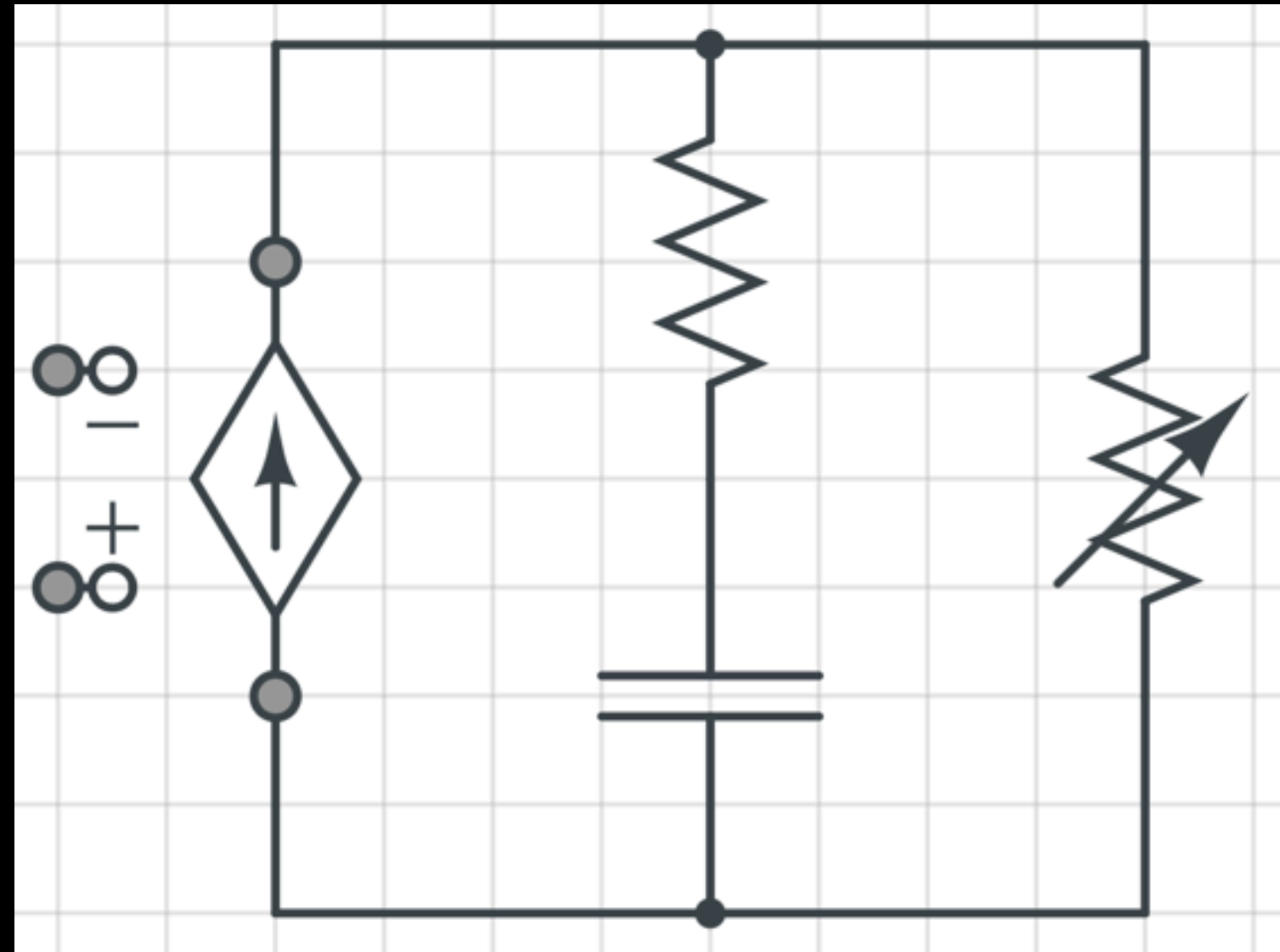
Energy harvester: Solar cell
Energy consumers: Variable resistor



Energy storage:
Energy buffer with
Equivalent series resistance

Energy Modeling

Energy harvester: Solar cell
 Energy consumers: Variable resistor



Energy storage:
 Energy buffer with
 Equivalent series resistance

Solar Array:

E : incident irradiance W/m^2
 A : solar array surface area
 e : solar array efficiency
 V_{oc} : open circuit voltage
 I_{sc} : short circuit current

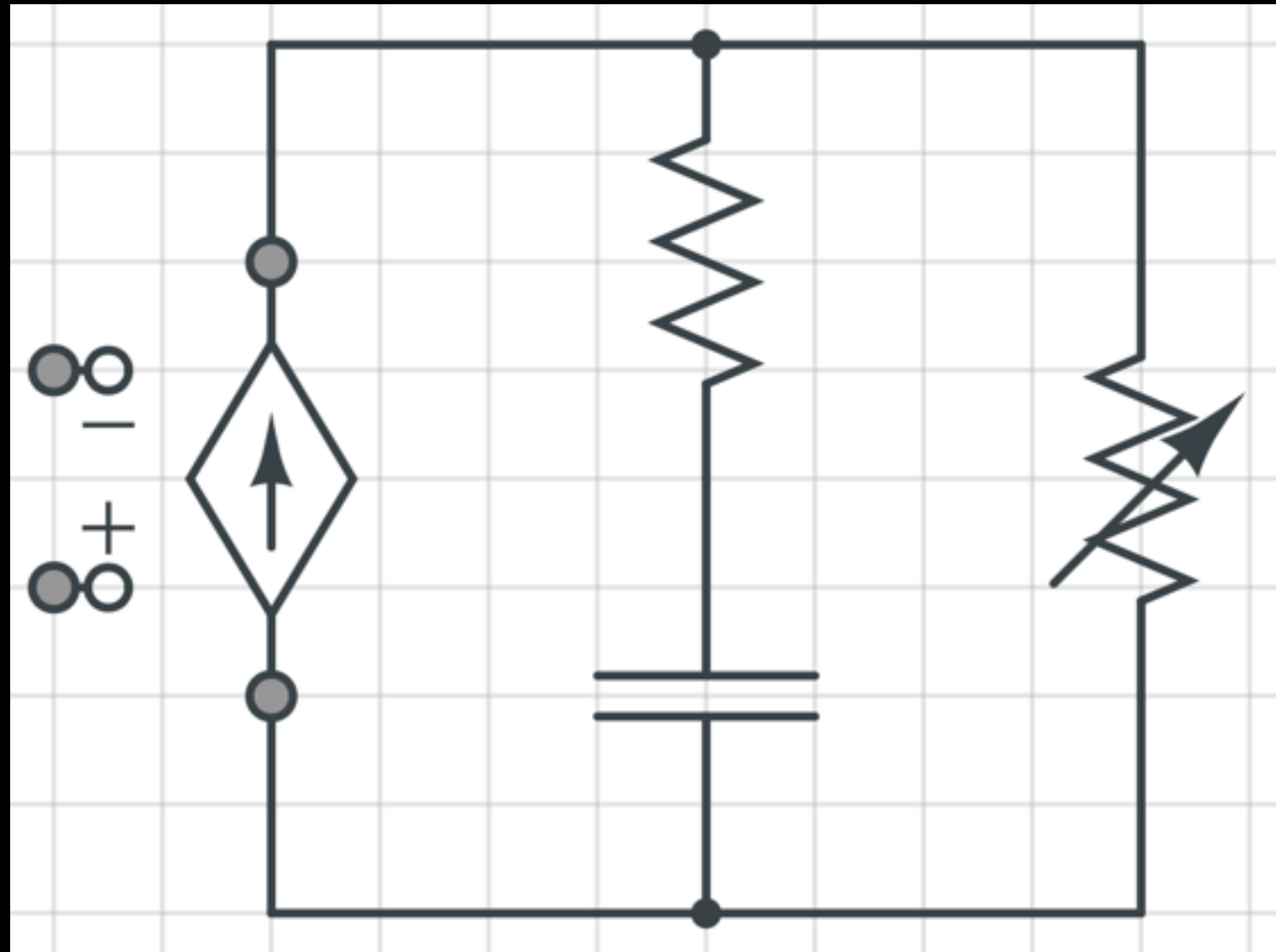
IV Curve



$$I_{SC} = E \cdot A \cdot e / V_{OC}$$

Energy Modeling

Energy harvester: Solar cell
Energy consumers: Variable resistor



Energy storage:
Energy buffer with
Equivalent series resistance

Solar Array:

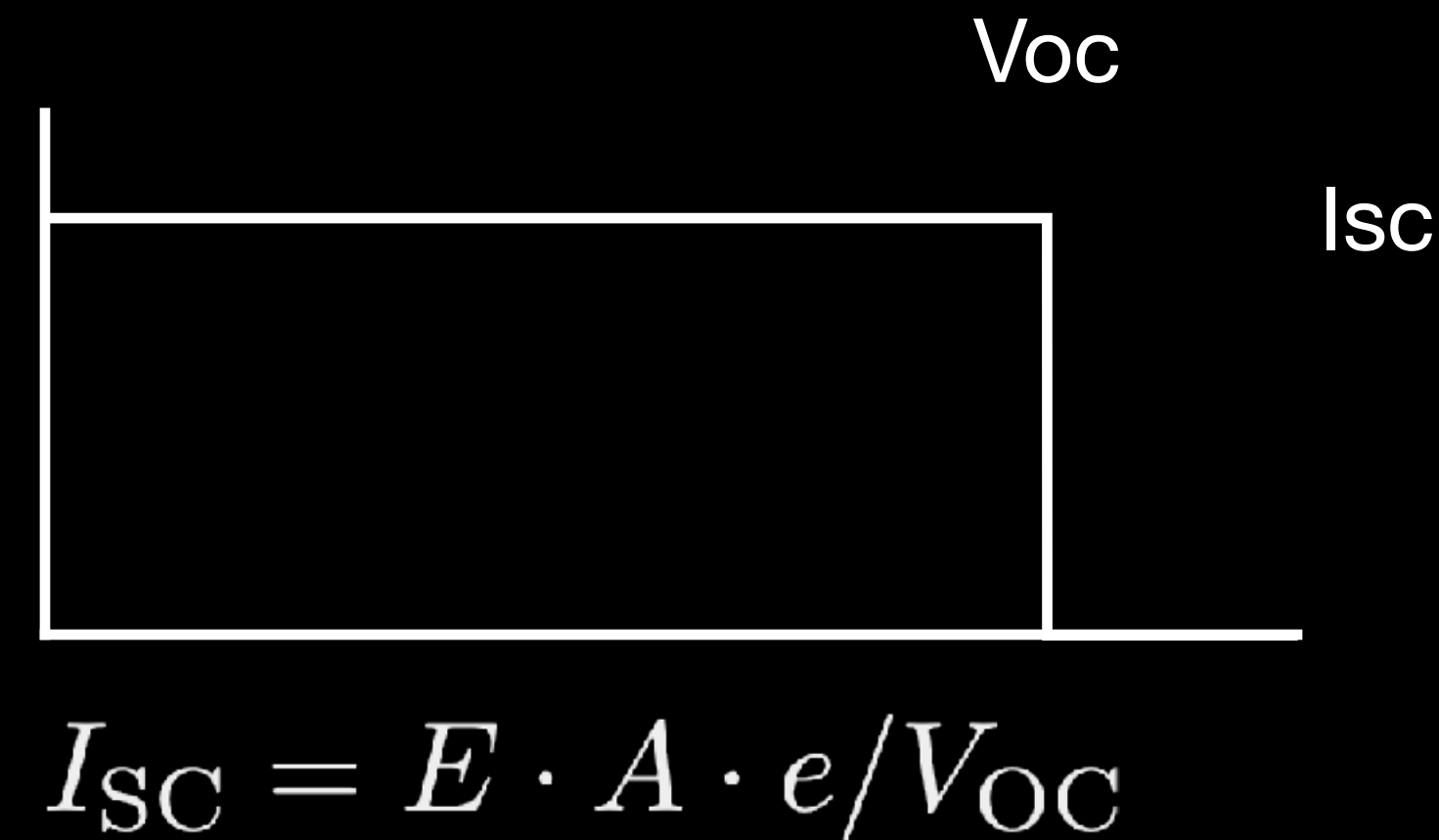
E : incident irradiance W/m^2
 A : solar array surface area
 e : solar array efficiency
 V_{oc} : open circuit voltage
 I_{sc} : short circuit current

Node Voltage $v(t)$:

$$2v(t) = \frac{q(t)}{C} + I_S R_{ESR} + \sqrt{\left(\frac{q(t)}{C} + I_S R_{ESR}\right)^2 - 4P_{MODE} R_{ESR}}$$

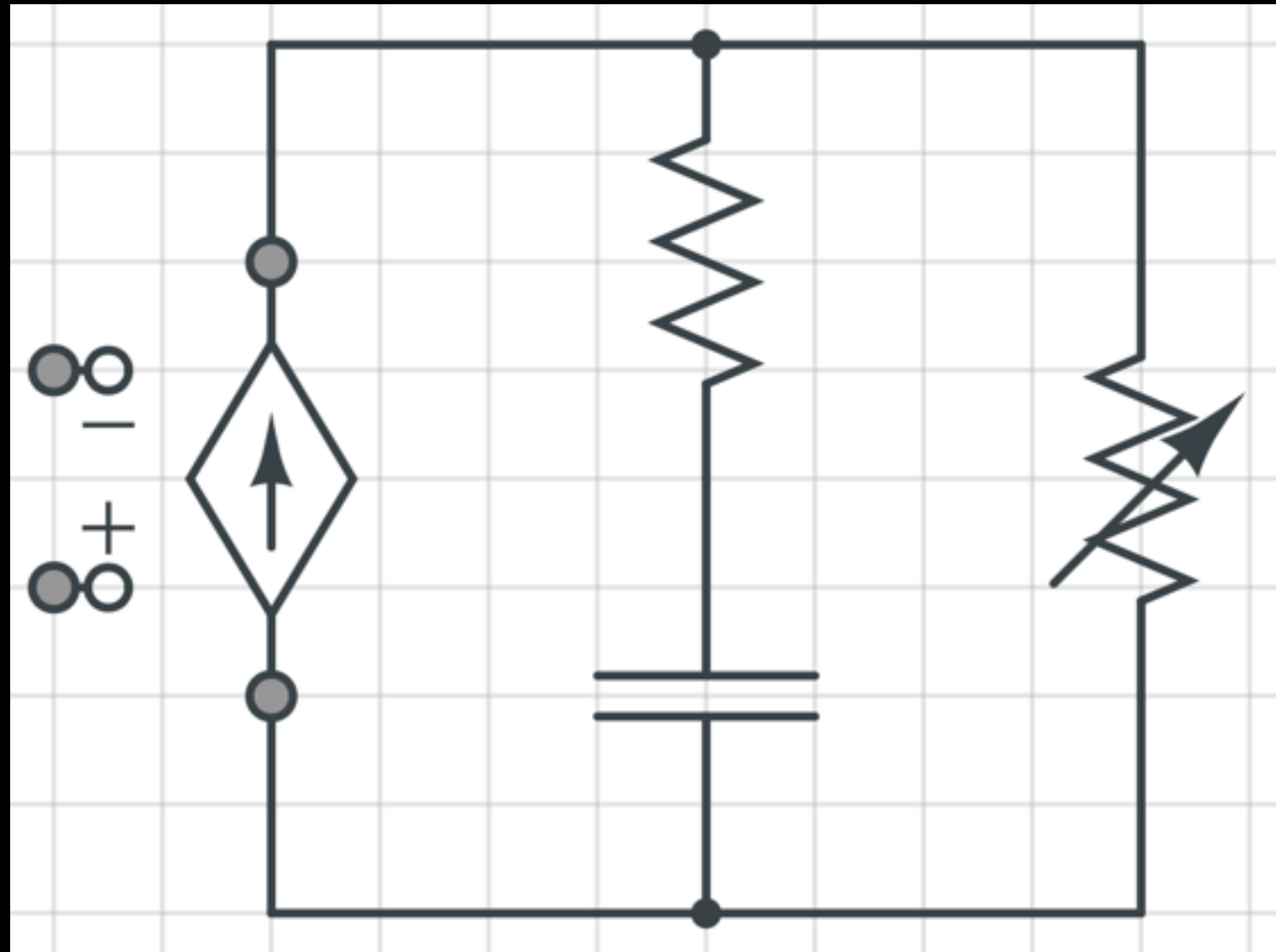
$q(t)$: buffer charge
 C : buffer capacitance
 I_S : solar array current
 R_{ESR} : capacitor ESR
 P_{MODE} : peripheral power draw

IV Curve



Energy Modeling

Energy harvester: Solar cell
Energy consumers: Variable resistor



Energy storage:
Energy buffer with
Equivalent series resistance

Solar Array:

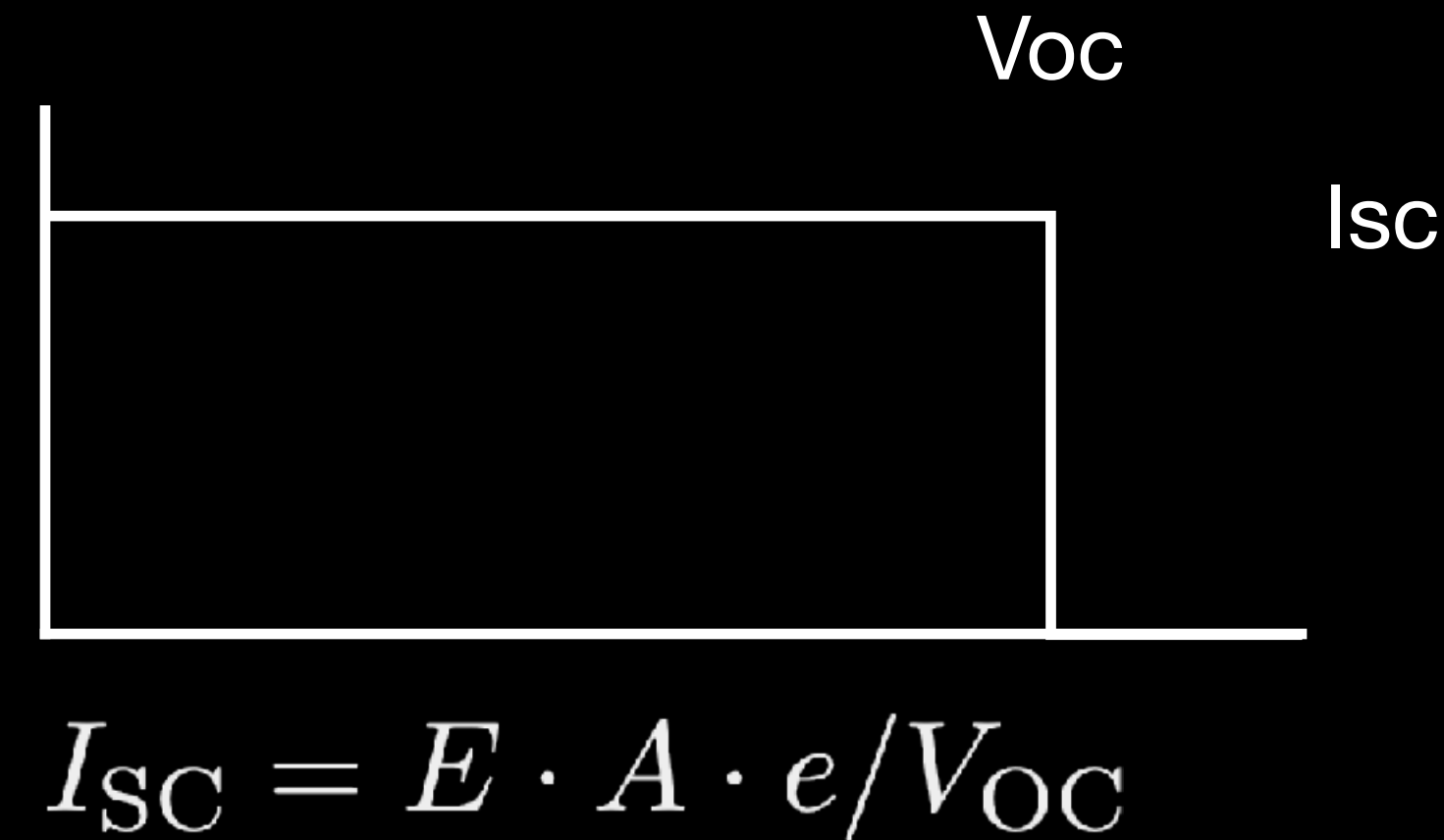
E : incident irradiance W/m^2
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IV Curve

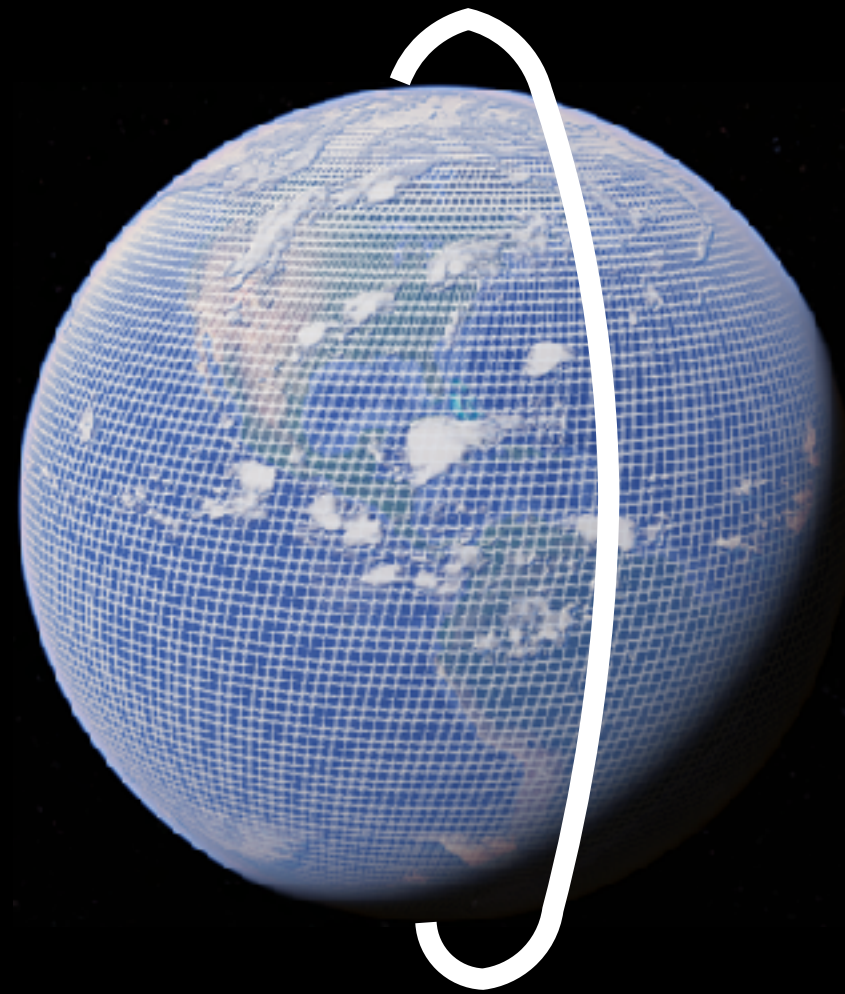


Energy consumers:

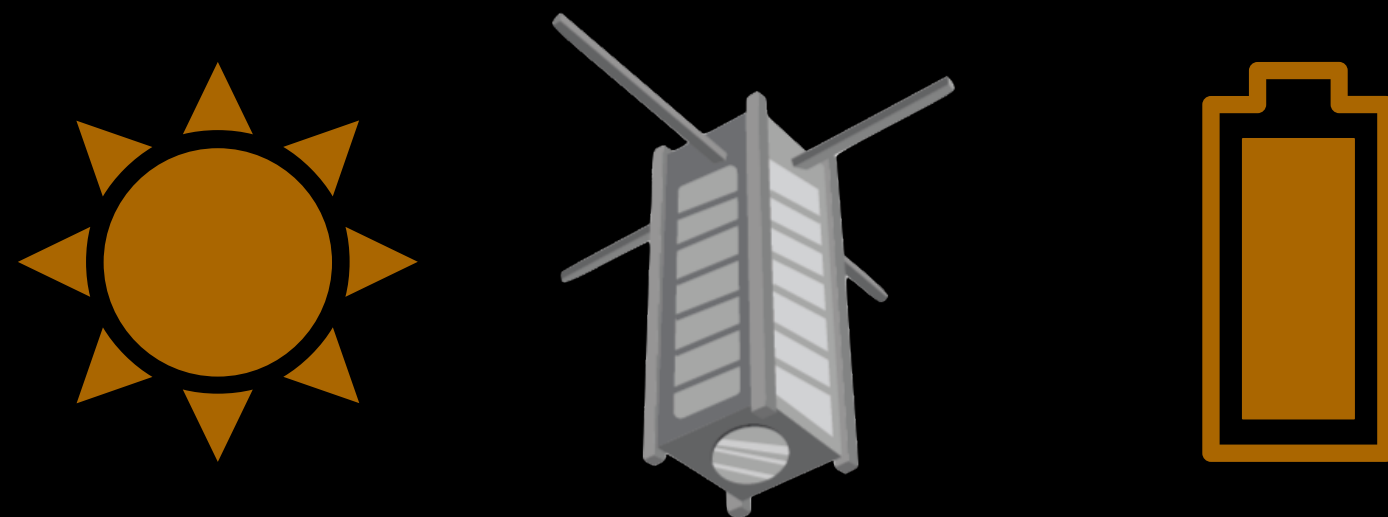
$$I_D = \frac{P_{MODE}}{v(t)}$$

Components of Space Simulation

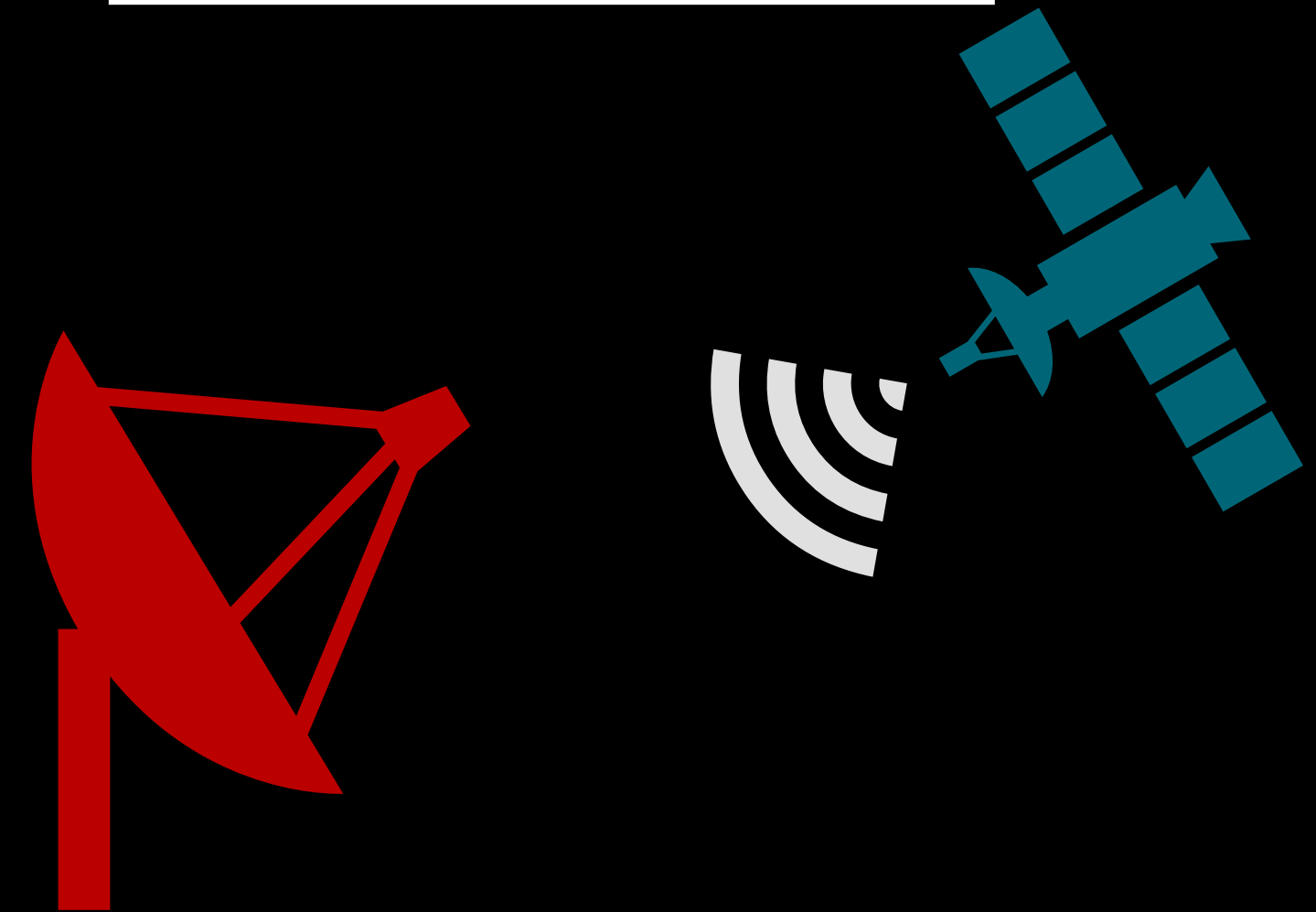
Orbital Mechanics



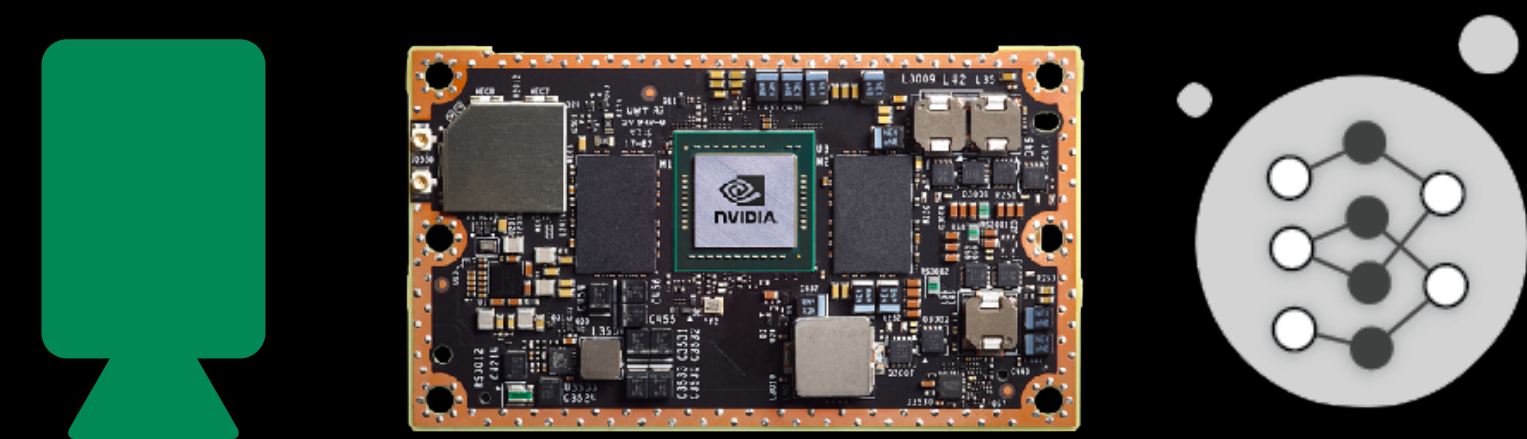
Energy and Power



Communication

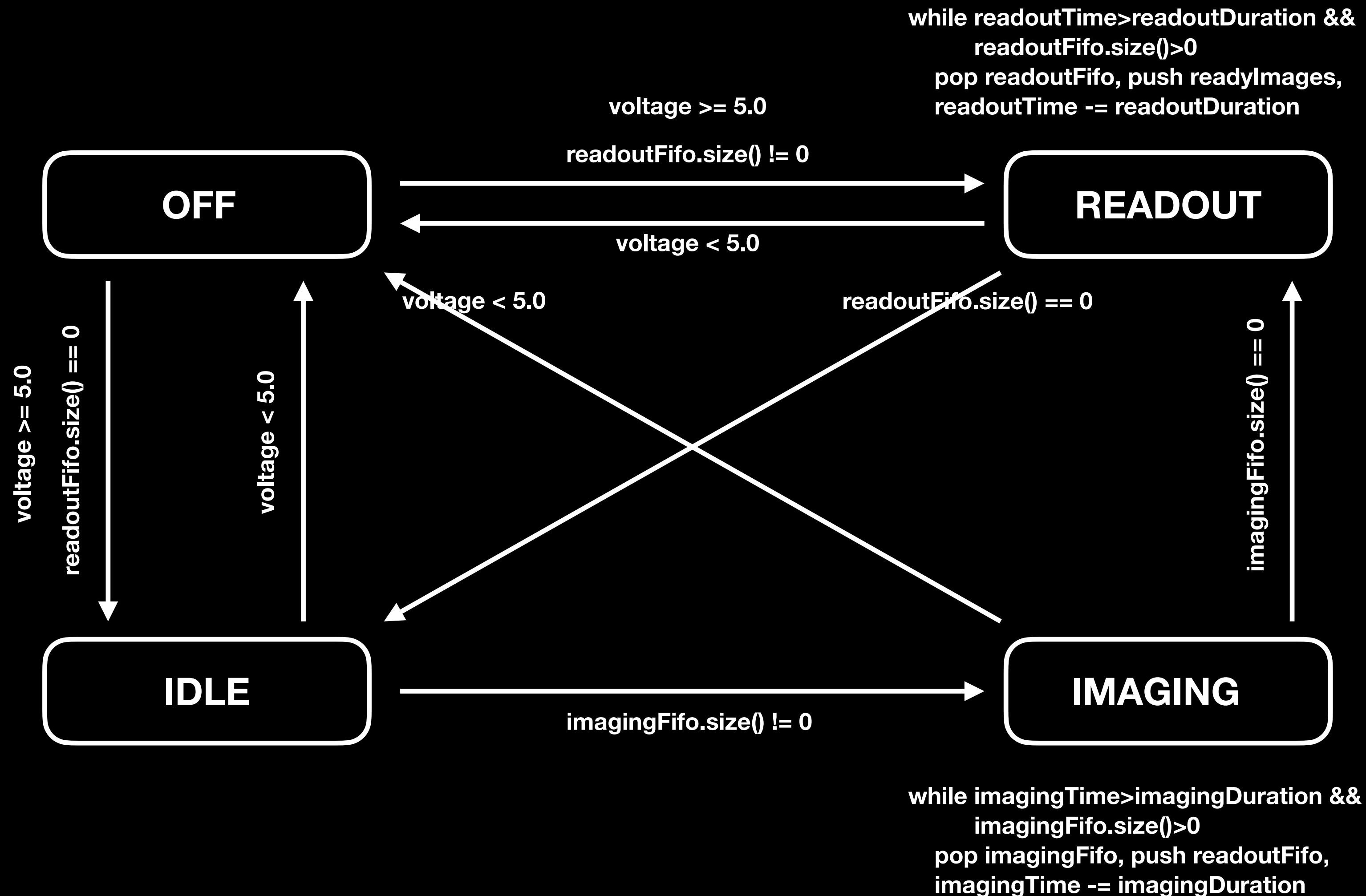


Satellite Subsystems



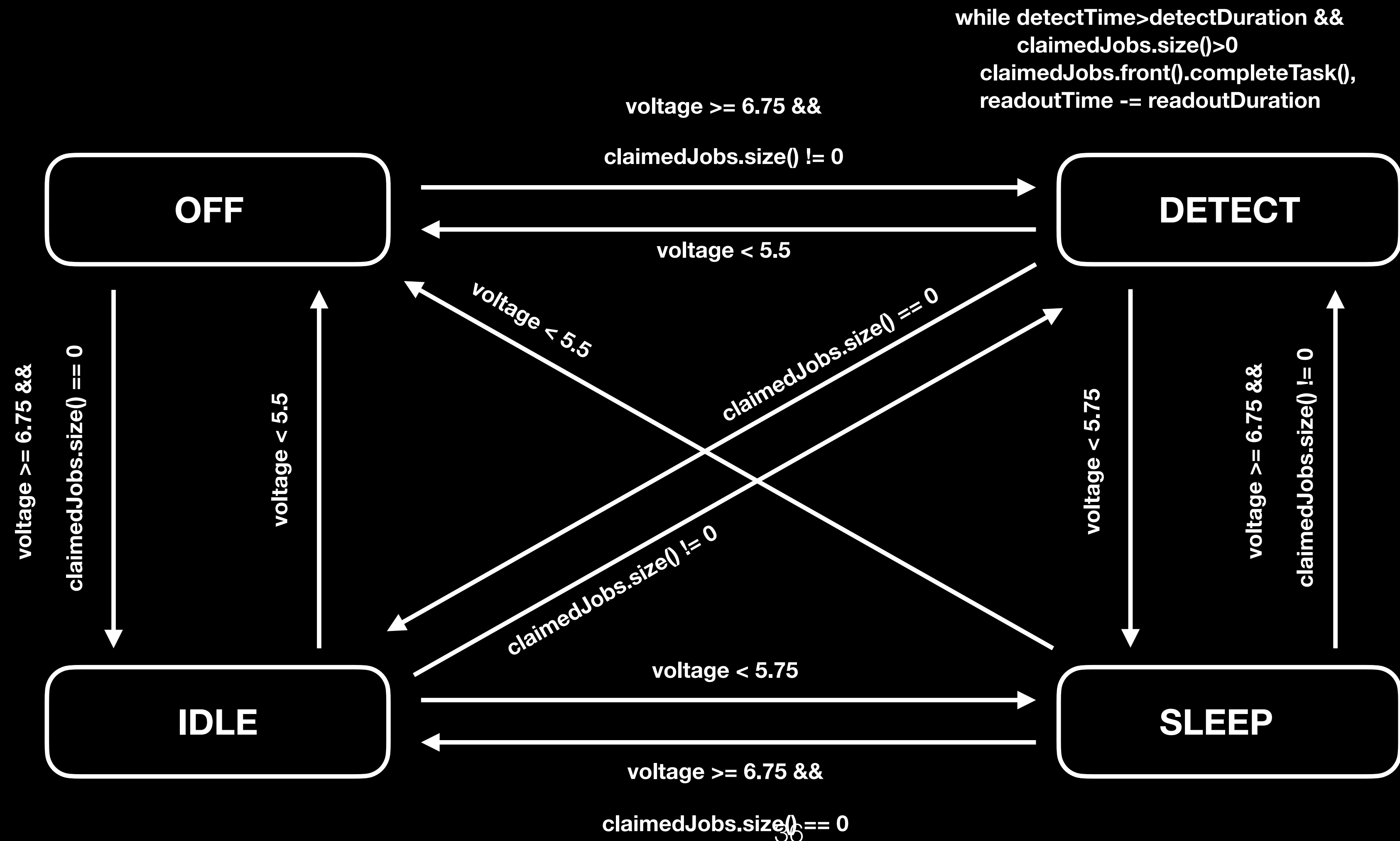
Camera Peripheral Modeling

Imager State Machine



Computing Peripheral Modeling

Processor State Machine



Other Space Simulation Components

Date and Time

Coordinate Frames

```
JD (I, J, K) = K - 32075 + 1461*(I + 4800 + (J - 14)/12)/4  
              + 367*(J - 2 - (J - 14)/12*12)/12 - 3  
              *((I + 4900 + (J - 14)/12)/100)/4
```

The authors have yet to discover the algorithm of comparable compactness for converting a Julian Date back to a calendar date. But in preference to leaving the problem undiscussed, the following is offered (presented as a FORTRAN subroutine):

```
SUBROUTINE DATE (JD, I, J, K)  
  L = JD + 68569  
  N = 4*L/146097  
  L = L - (146097*N + 3)/4  
  I = 4000*(L + 1)/1461001  
  L = L - 1461*I/4 + 31  
  J = 80*L/2447  
  K = L - 2447*J/80  
  L = J/11  
  J = J + 2 - 12*L  
  I = 100*(N - 49) + I + L  
  RETURN  
END
```

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AND
THOMAS C. VAN FLANDERN
*U.S. Naval Observatory
Washington, DC 20390*

Other Space Simulation Components

Date and Time

```
JD (I, J, K) = K - 32075 + 1461*(I + 4800 + (J - 14)/12)/4  
+ 367*(J - 2 - (J - 14)/12*12)/12 - 3  
*((I + 4900 + (J - 14)/12)/100)/4
```

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```

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Volume 11 / Number 10 / October, 1968

Coordinate Frames

- ECI: Earth-centered inertial
 - (x,y,z) 3D coordinate frame
 - Useful for representing satellite locations
- LLH: Latitude, longitude, and height above the ellipsoid
 - Useful for placing ground stations
- SEZ: South, East, and z-direction
 - Useful for ground station views of satellites above the horizon

Overview

Background and Related Work

Components of Space Simulation

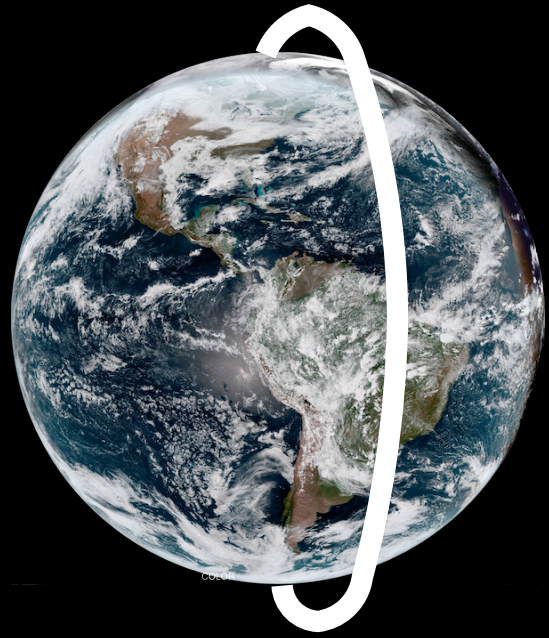
The cote Workflow

Example Programs in cote

The cote Workflow

The cote Workflow

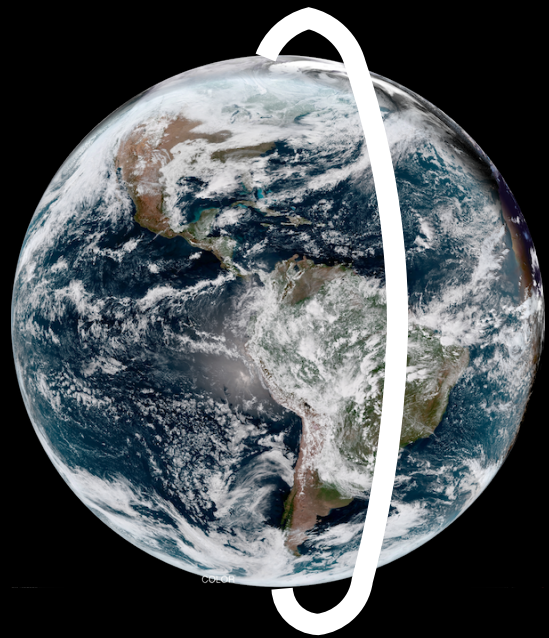
Simulator Inputs



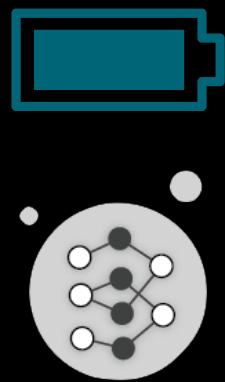
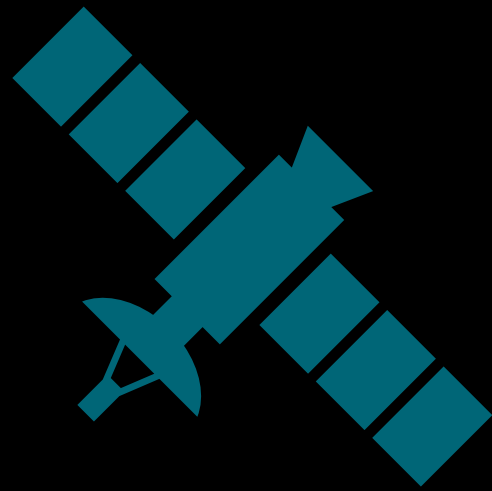
**Orbital Mechanics
Configuration**

The cote Workflow

Simulator Inputs



**Orbital Mechanics
Configuration**

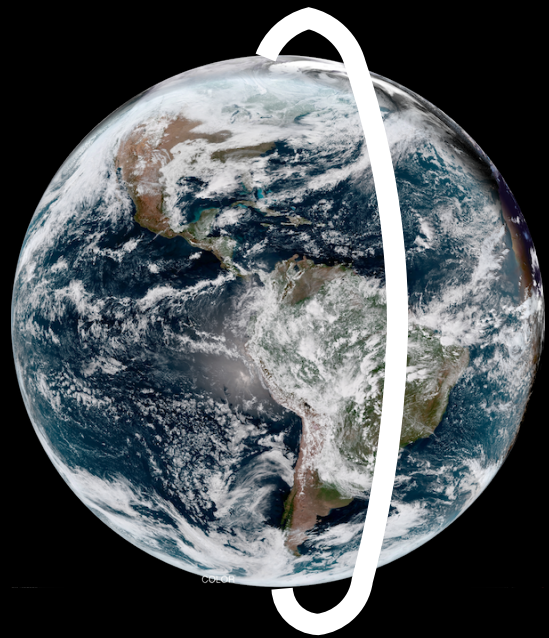


Satellite Configuration:

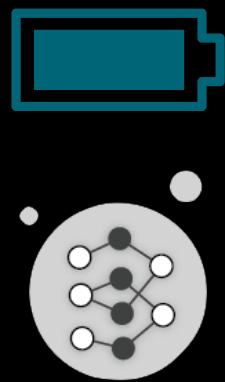
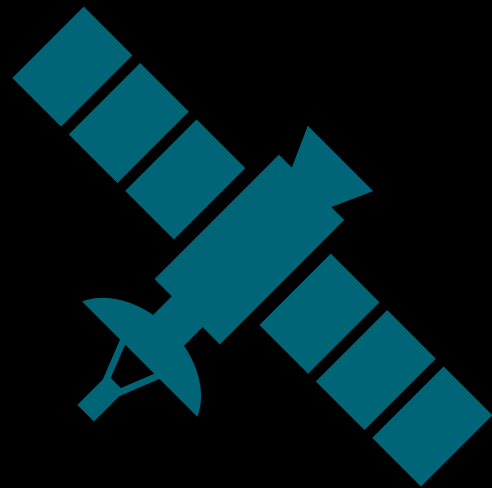
- Energy System
- Onboard Processing
- Other Peripherals

The cote Workflow

Simulator Inputs

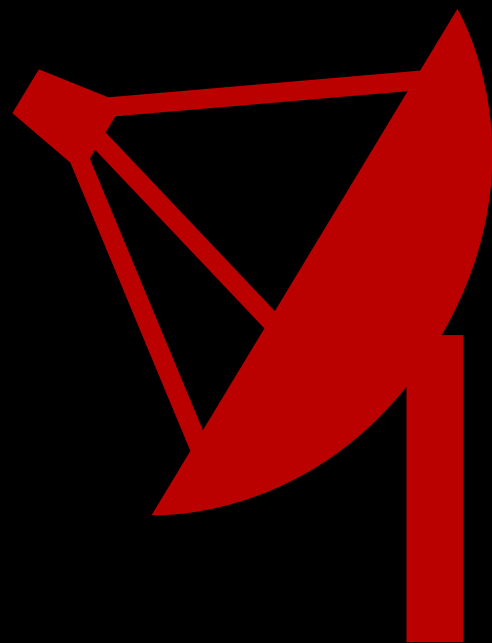


**Orbital Mechanics
Configuration**



Satellite Configuration:

- Energy System
- Onboard Processing
- Other Peripherals



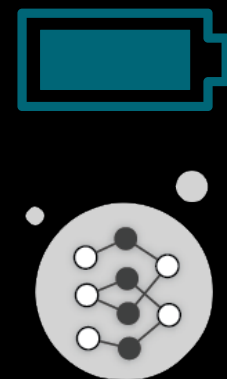
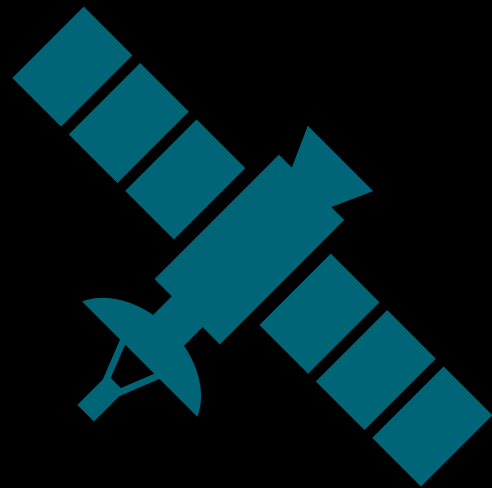
**Communications
Configuration**

The cote Workflow

Simulator Inputs

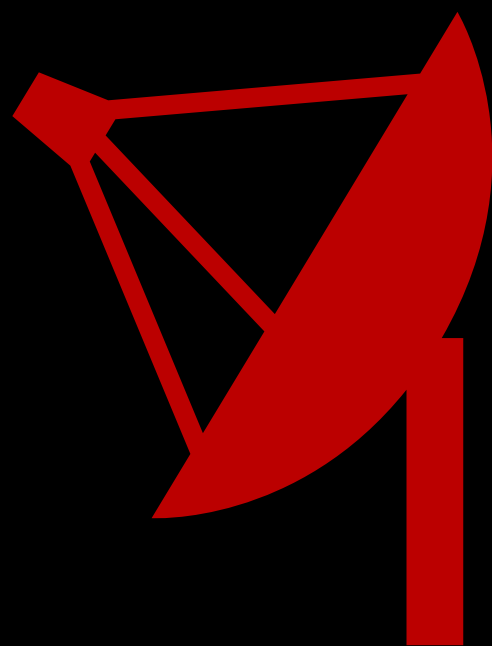


**Orbital Mechanics
Configuration**



Satellite Configuration:

- Energy System
- Onboard Processing
- Other Peripherals



**Communications
Configuration**

Simulator Outputs

**Scenario
Simulation**

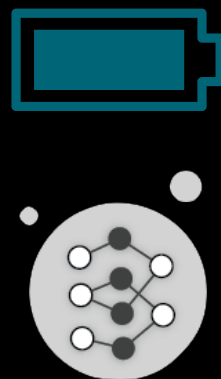
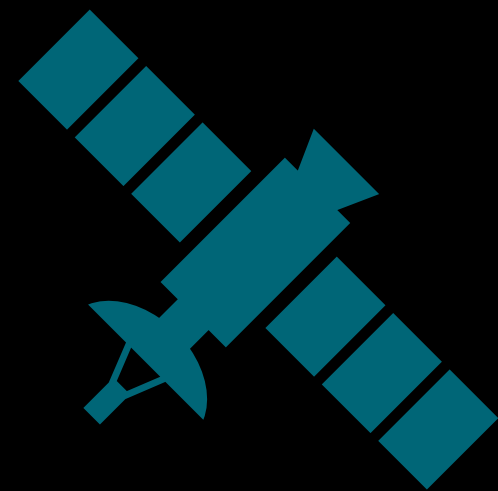


The cote Workflow

Simulator Inputs

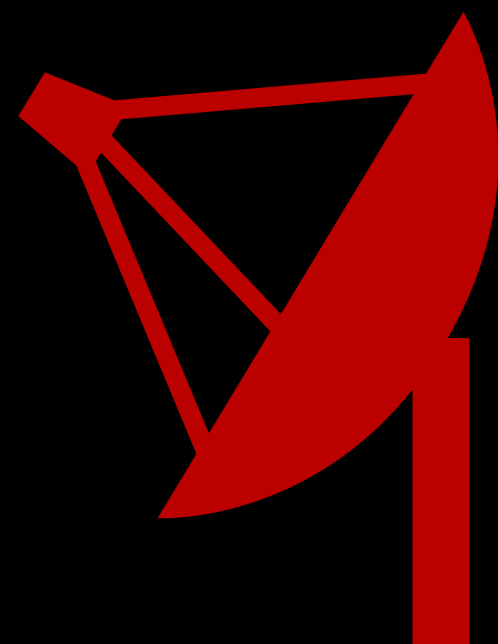


**Orbital Mechanics
Configuration**



Satellite Configuration:

- Energy System
- Onboard Processing
- Other Peripherals



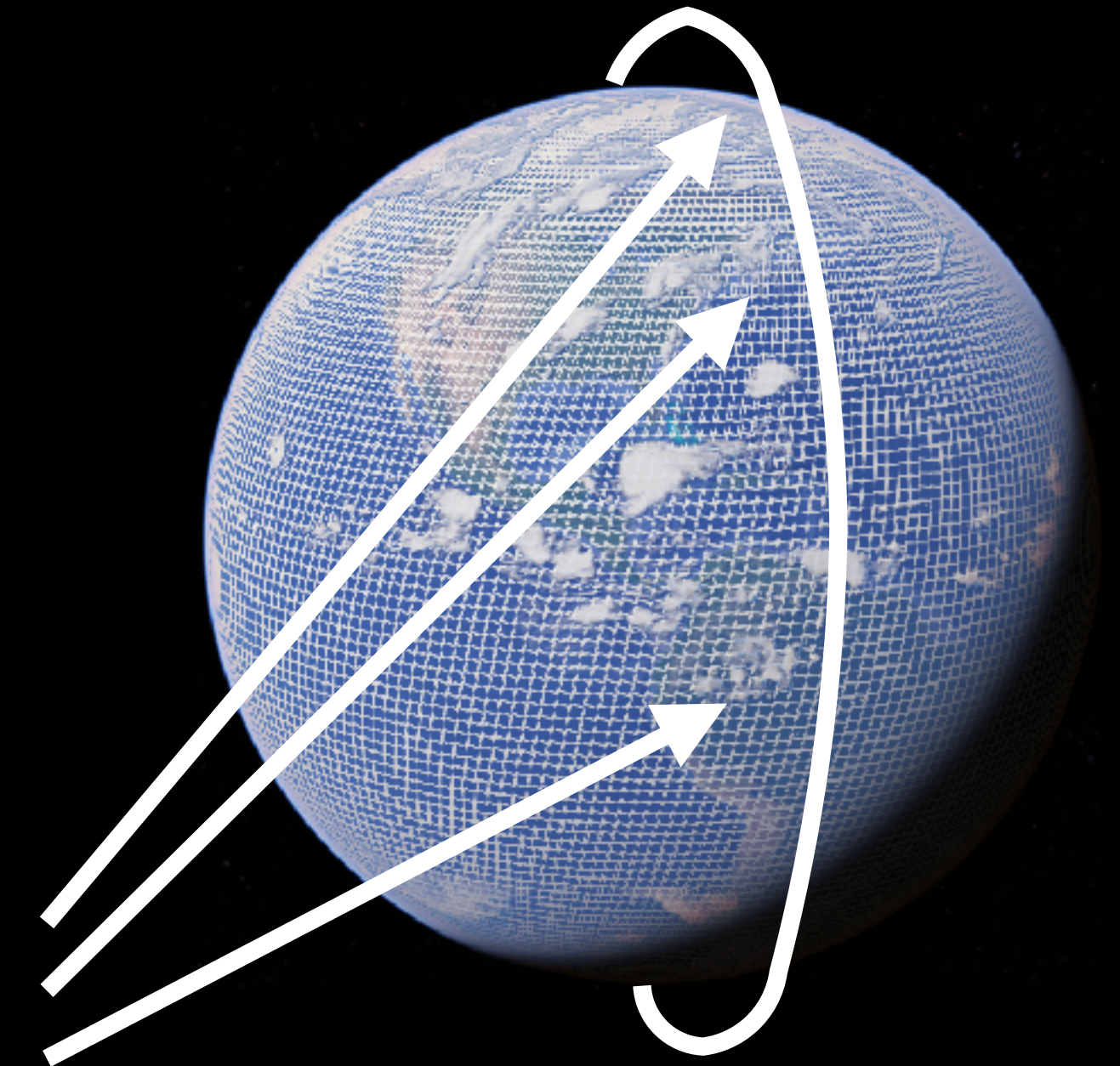
**Communications
Configuration**

Simulator Outputs

**Scenario
Simulation**

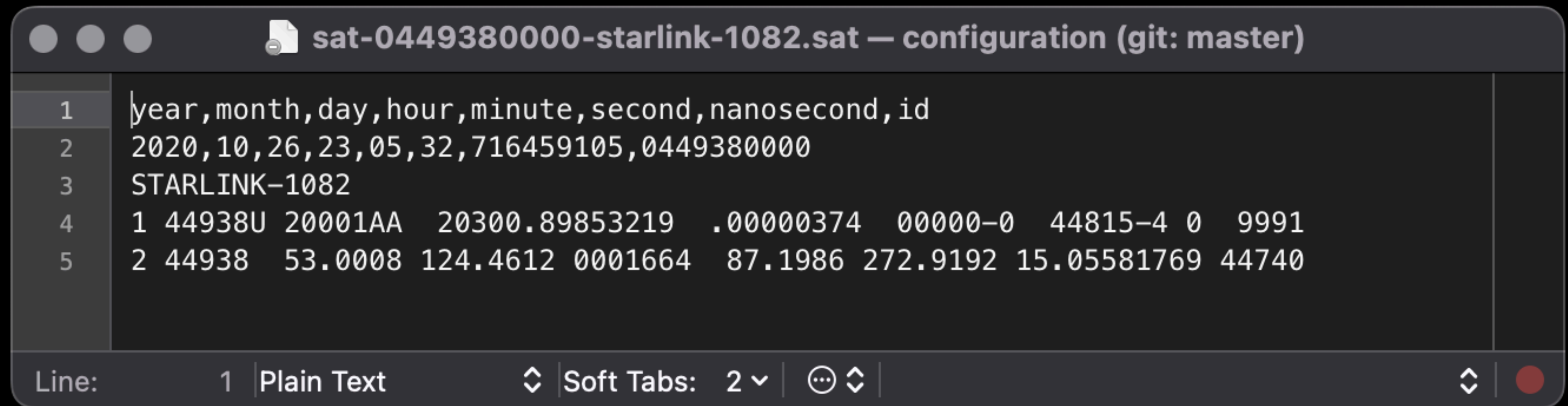


Event Traces



**Observation Dates and Times
Satellite Activity Traces
Communication Logs**

Example Satellite Config. File



The image shows a code editor window with a dark theme. The title bar at the top reads "sat-0449380000-starlink-1082.sat — configuration (git: master)". The editor contains five lines of text, with line numbers 1 through 5 visible in the left margin. The text is as follows:

```
1 |year,month,day,hour,minute,second,nanosecond,id
2 |2020,10,26,23,05,32,716459105,0449380000
3 |STARLINK-1082
4 |1 44938U 20001AA 20300.89853219 .00000374 00000-0 44815-4 0 9991
5 |2 44938 53.0008 124.4612 0001664 87.1986 272.9192 15.05581769 44740
```

At the bottom of the editor, there is a status bar. It shows "Line: 1" followed by a dropdown menu currently set to "Plain Text". To the right of this are icons for undo and redo, followed by "Soft Tabs: 2" with a dropdown arrow. Further right are icons for search, replace, and a red circle icon.

Example Satellite Config. File

Satellite Epoch

```
1 year,month,day,hour,minute,second,nanosecond,id
2 2020,10,26,23,05,32,716459105,0449380000
3 STARLINK-1082
4 1 44938U 20001AA 20300.89853219 .00000374 00000-0 44815-4 0 9991
5 2 44938 53.0008 124.4612 0001664 87.1986 272.9192 15.05581769 44740
```

Line: 1 | Plain Text | Soft Tabs: 2

Example Satellite Config. File

Satellite Epoch

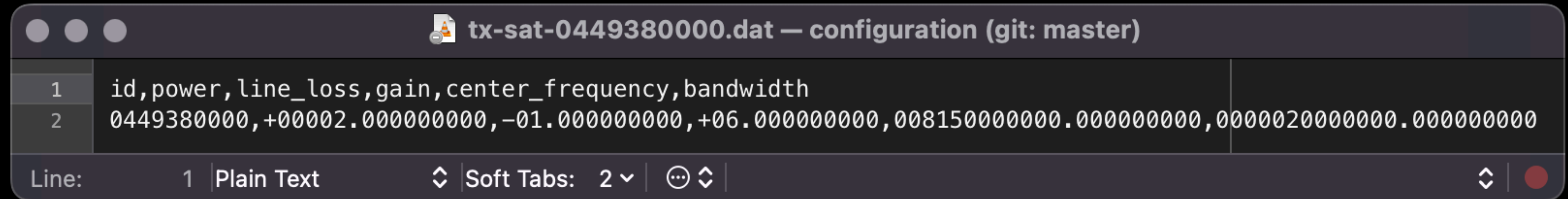
```
sat-0449380000-starlink-1082.sat — configuration (git: master)
1 | year,month,day,hour,minute,second,nanosecond,id
2 | 2020,10,26,23,05,32,716459105,0449380000
3 | STARLINK-1082
4 | 1 44938U 20001AA 20300.89853219 .00000374 00000-0 44815-4 0 9991
5 | 2 44938 53.0008 124.4612 0001664 87.1986 272.9192 15.05581769 44740
```

Line: 1 | Plain Text | Soft Tabs: 2 |

Satellite TLE

Example Comms. Config. Files

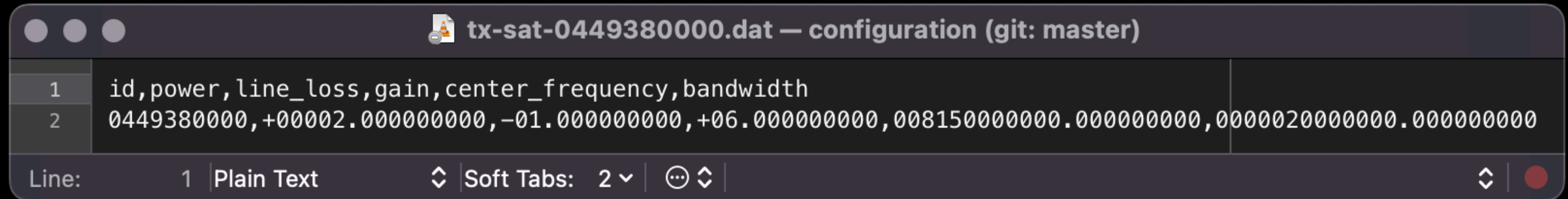
Example Comms. Config. Files



The screenshot shows a code editor window with a title bar that reads "tx-sat-0449380000.dat — configuration (git: master)". The editor contains two lines of text. Line 1 is a header: "id,power,line_loss,gain,center_frequency,bandwidth". Line 2 is a data row: "0449380000,+00002.000000000,-01.000000000,+06.000000000,008150000000.000000000,0000020000000.000000000". The editor has a line number column on the left with numbers 1 and 2. At the bottom, there is a status bar that says "Line: 1 | Plain Text" and "Soft Tabs: 2" with a dropdown arrow. There are also icons for undo, redo, and a search icon.

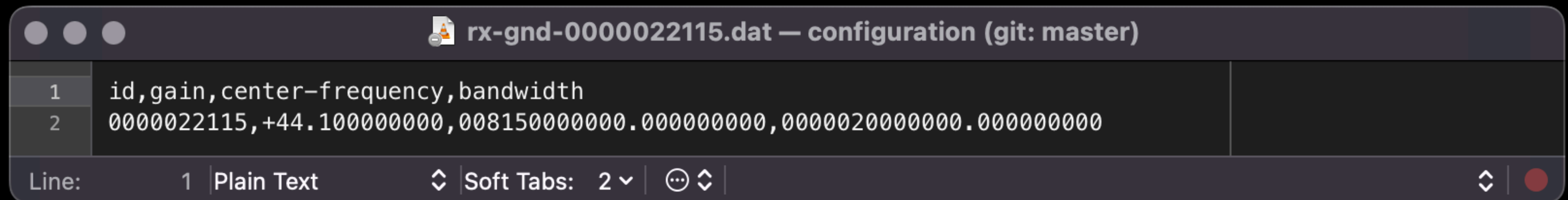
id,power,line_loss,gain,center_frequency,bandwidth
0449380000,+00002.000000000,-01.000000000,+06.000000000,008150000000.000000000,0000020000000.000000000

Example Comms. Config. Files



```
1 id,power,line_loss,gain,center_frequency,bandwidth
2 0449380000,+00002.000000000,-01.000000000,+06.000000000,00815000000.000000000,0000020000000.000000000
```

Line: 1 Plain Text ↕ Soft Tabs: 2 ▾ ⋮ ↕



```
1 id,gain,center-frequency,bandwidth
2 0000022115,+44.100000000,00815000000.000000000,0000020000000.000000000
```

Line: 1 Plain Text ↕ Soft Tabs: 2 ▾ ⋮ ↕

Example Comms. Config. Files

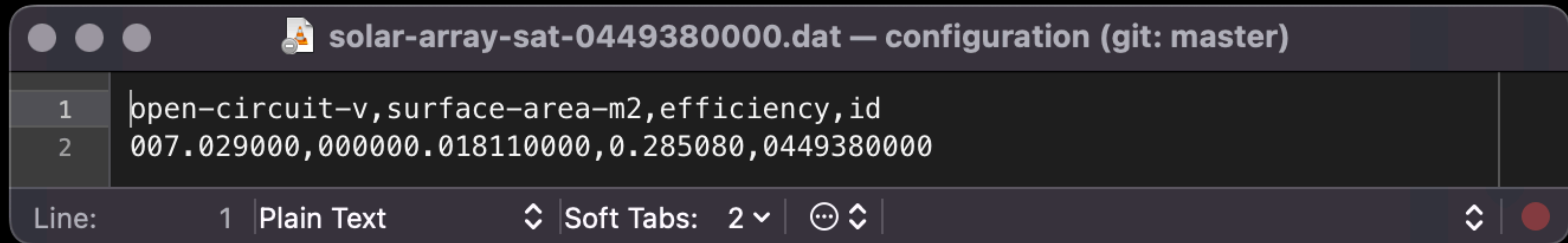
```
tx-sat-0449380000.dat — configuration (git: master)
1 id,power,line_loss,gain,center_frequency,bandwidth
2 0449380000,+00002.000000000,-01.000000000,+06.000000000,00815000000.000000000,000002000000.000000000
Line: 1 Plain Text Soft Tabs: 2
```

```
rx-gnd-0000022115.dat — configuration (git: master)
1 id,gain,center-frequency,bandwidth
2 0000022115,+44.100000000,00815000000.000000000,000002000000.000000000
Line: 1 Plain Text Soft Tabs: 2
```

```
gnd-0000022115-the-university-of-hong-kong.gnd — configuration (git: master)
1 id,lat,lon,hae-km
2 0000022115,+22.283888889,+114.138055556,+00.000000000
Line: 1 Plain Text Soft Tabs: 2
```


Example Energy Config. Files

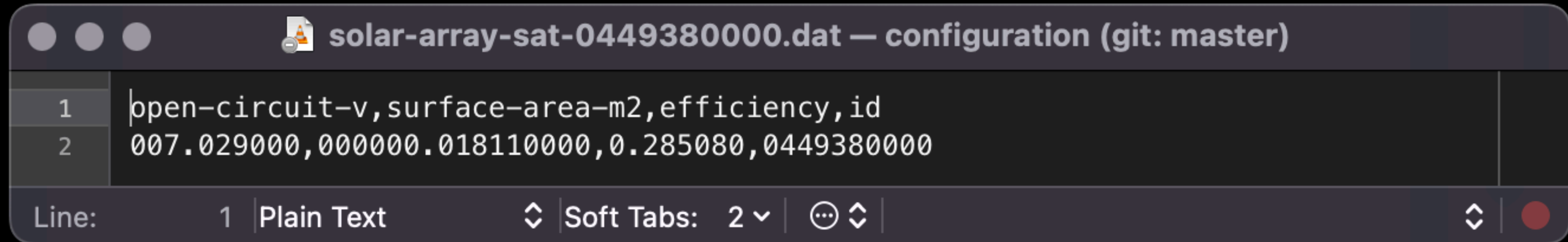
Example Energy Config. Files



The screenshot shows a code editor window with a title bar that reads "solar-array-sat-0449380000.dat — configuration (git: master)". The editor contains two lines of text: "open-circuit-v,surface-area-m2,efficiency,id" on line 1 and "007.029000,000000.018110000,0.285080,0449380000" on line 2. The status bar at the bottom indicates "Line: 1", "Plain Text", "Soft Tabs: 2", and includes icons for undo, redo, and a search icon.

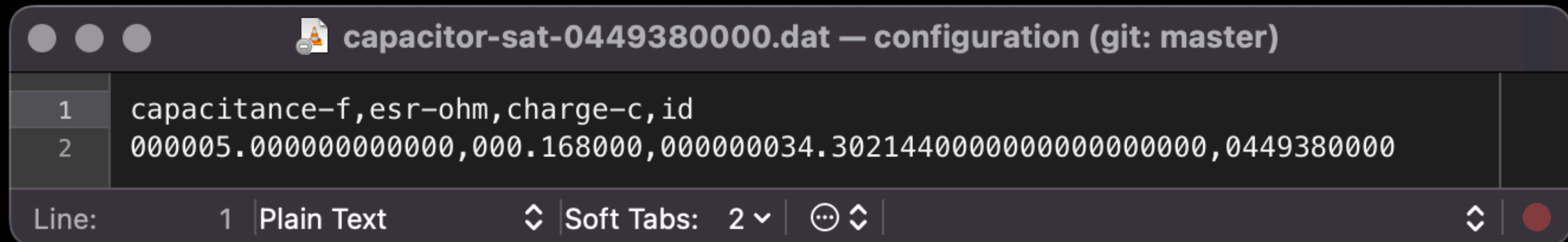
```
1 open-circuit-v,surface-area-m2,efficiency,id
2 007.029000,000000.018110000,0.285080,0449380000
```


Example Energy Config. Files



```
1 open-circuit-v,surface-area-m2,efficiency,id
2 007.029000,000000.018110000,0.285080,0449380000
```

Line: 1 Plain Text Soft Tabs: 2

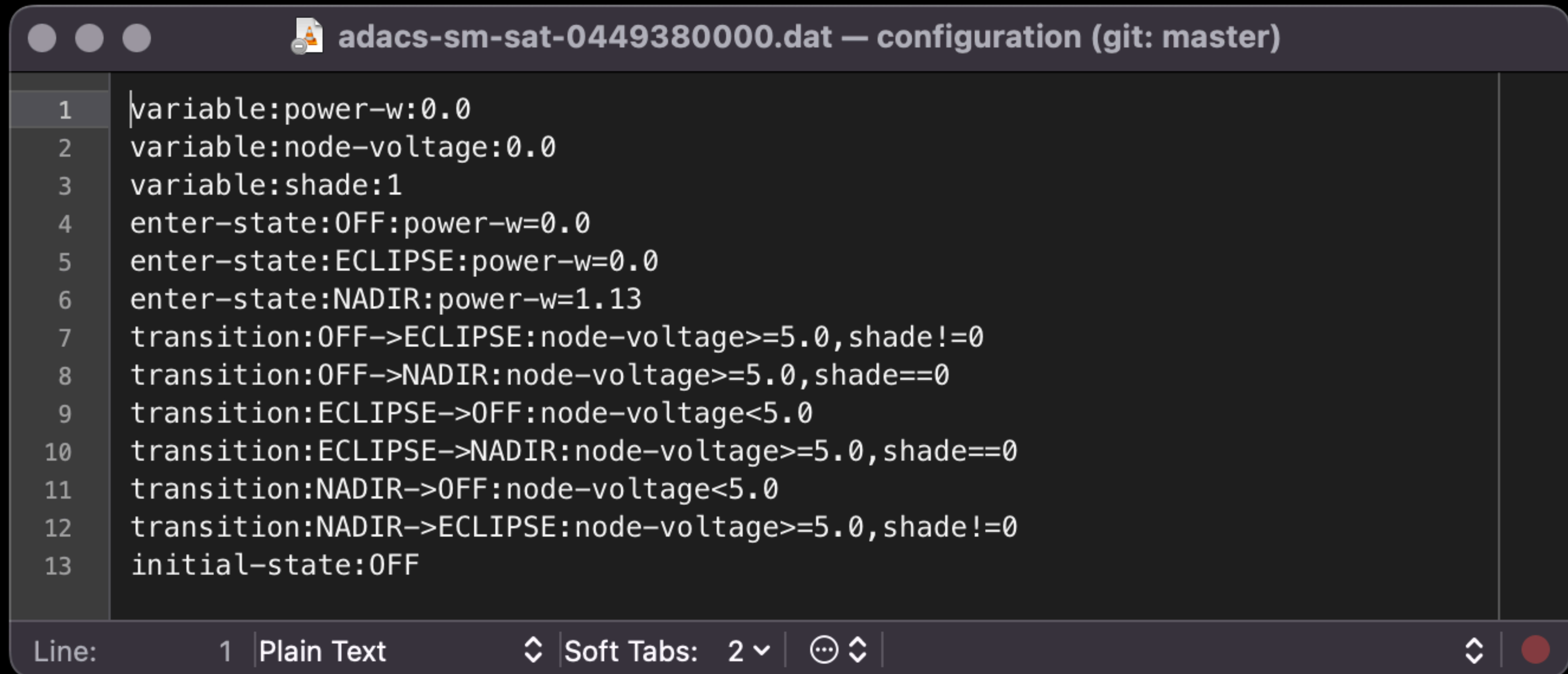


```
1 capacitance-f,esr-ohm,charge-c,id
2 000005.000000000000,000.168000,000000034.3021440000000000000000,0449380000
```

Line: 1 Plain Text Soft Tabs: 2

Example Subsystem Config. Files

Three-state ADACS State Machine



The image shows a code editor window with a dark theme. The title bar at the top reads "adacs-sm-sat-0449380000.dat — configuration (git: master)". The editor contains 13 lines of text, each preceded by a line number from 1 to 13. The text defines a state machine with three states: OFF, ECLIPSE, and NADIR. It includes variable declarations for power, node-voltage, and shade, and transition rules based on node-voltage and shade values. The initial state is OFF.

```
1 variable:power-w:0.0
2 variable:node-voltage:0.0
3 variable:shade:1
4 enter-state:OFF:power-w=0.0
5 enter-state:ECLIPSE:power-w=0.0
6 enter-state:NADIR:power-w=1.13
7 transition:OFF->ECLIPSE:node-voltage>=5.0,shade!=0
8 transition:OFF->NADIR:node-voltage>=5.0,shade==0
9 transition:ECLIPSE->OFF:node-voltage<5.0
10 transition:ECLIPSE->NADIR:node-voltage>=5.0,shade==0
11 transition:NADIR->OFF:node-voltage<5.0
12 transition:NADIR->ECLIPSE:node-voltage>=5.0,shade!=0
13 initial-state:OFF
```

At the bottom of the editor, there is a status bar. It shows "Line: 1", "Plain Text", "Soft Tabs: 2", and several icons for editing and navigation.

Example Subsystem Config. Files

Imager peripheral:

```
1 |constant:imaging-duration-s:0.031260
2 |constant:readout-duration-s:0.838860
3 |variable:imaging-time-s:0.0
4 |variable:readout-time-s:0.0
5 |variable:power-w:0.0
6 |variable:node-voltage:0.0
7 |variable:imaging-task-count:0
8 |variable:readout-task-count:0
9 |variable:ready-images:0
10|enter-state:OFF:power-w=0.0
11|enter-state:IDLE:power-w=0.0
12|enter-state:IMAGING:power-w=3.5
13|enter-state:READOUT:power-w=2.5
14|exit-state:IMAGING:imaging-time-s=0.0
15|transition:OFF->READOUT:node-voltage>=5.0,readout-task-count!=0
16|transition:OFF->IDLE:node-voltage>=5.0,readout-task-count==0
17|transition:IDLE->OFF:node-voltage<5.0
18|transition:IDLE->IMAGING:node-voltage>=5.0,imaging-task-count!=0
19|transition:IMAGING->OFF:node-voltage<5.0:imaging-task-count=0
20|transition:IMAGING->READOUT:node-voltage>=5.0,imaging-task-count==0
21|transition:READOUT->OFF:node-voltage<5.0
22|transition:READOUT->IDLE:node-voltage>=5.0,readout-task-count==0:readout-time-s=0.0
23|initial-state:OFF
24
```


Example Subsystem Config. Files

Processor peripheral
running object
detection workload:

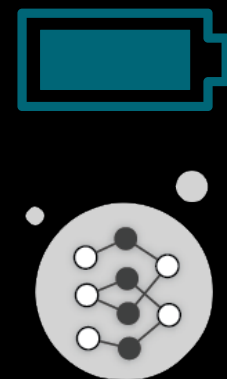
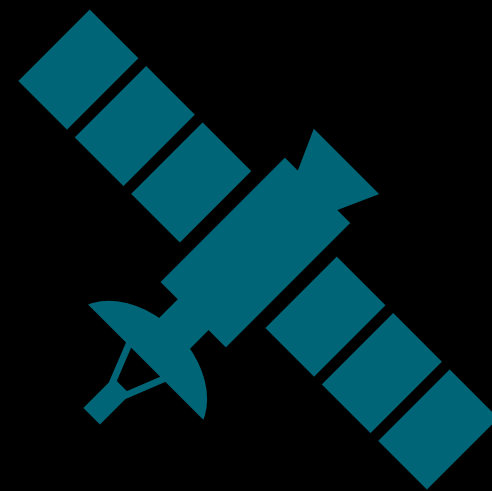
```
1 constant:task-duration-s:0.044860
2 variable:work-time-s:0.0
3 variable:power-w:0.0
4 variable:node-voltage:0.0
5 variable:claimed-task-count:0
6 variable:transmitting:0
7 enter-state:OFF:power-w=0.0
8 enter-state:SLEEP:power-w=0.5
9 enter-state:IDLE:power-w=0.5
10 enter-state:PAUSE:power-w=0.5
11 enter-state:WORK:power-w=11.3272
12 exit-state:WORK:work-time-s=0.0
13 transition:OFF->IDLE:node-voltage>=6.75,claimed-task-count==0
14 transition:OFF->PAUSE:node-voltage>=6.75,claimed-task-count!=0,transmitting!=0
15 transition:OFF->WORK:node-voltage>=6.75,claimed-task-count!=0,transmitting==0
16 transition:SLEEP->OFF:node-voltage<5.5
17 transition:SLEEP->IDLE:node-voltage>=6.75,claimed-task-count==0
18 transition:SLEEP->PAUSE:node-voltage>=6.75,claimed-task-count!=0,transmitting!=0
19 transition:SLEEP->WORK:node-voltage>=6.75,claimed-task-count!=0,transmitting==0
20 transition:IDLE->OFF:node-voltage<5.5
21 transition:IDLE->SLEEP:node-voltage<5.75,node-voltage>=5.5
22 transition:IDLE->PAUSE:node-voltage>=5.75,claimed-task-count!=0,transmitting!=0
23 transition:IDLE->WORK:node-voltage>=5.75,claimed-task-count!=0,transmitting==0
24 transition:PAUSE->OFF:node-voltage<5.5
25 transition:PAUSE->SLEEP:node-voltage<5.75,node-voltage>=5.5
26 transition:PAUSE->IDLE:node-voltage>=5.75,claimed-task-count==0
27 transition:PAUSE->WORK:node-voltage>=5.75,claimed-task-count!=0,transmitting==0
28 transition:WORK->OFF:node-voltage<5.5
29 transition:WORK->SLEEP:node-voltage<5.75,node-voltage>=5.5
30 transition:WORK->IDLE:node-voltage>=5.75,claimed-task-count==0
31 transition:WORK->PAUSE:node-voltage>=5.75,claimed-task-count!=0,transmitting!=0
32 initial-state:OFF
33
```


The cote Workflow

Simulator Inputs



Orbital Mechanics Configuration



Satellite Configuration:

- Energy System
- Onboard Processing
- Other Peripherals



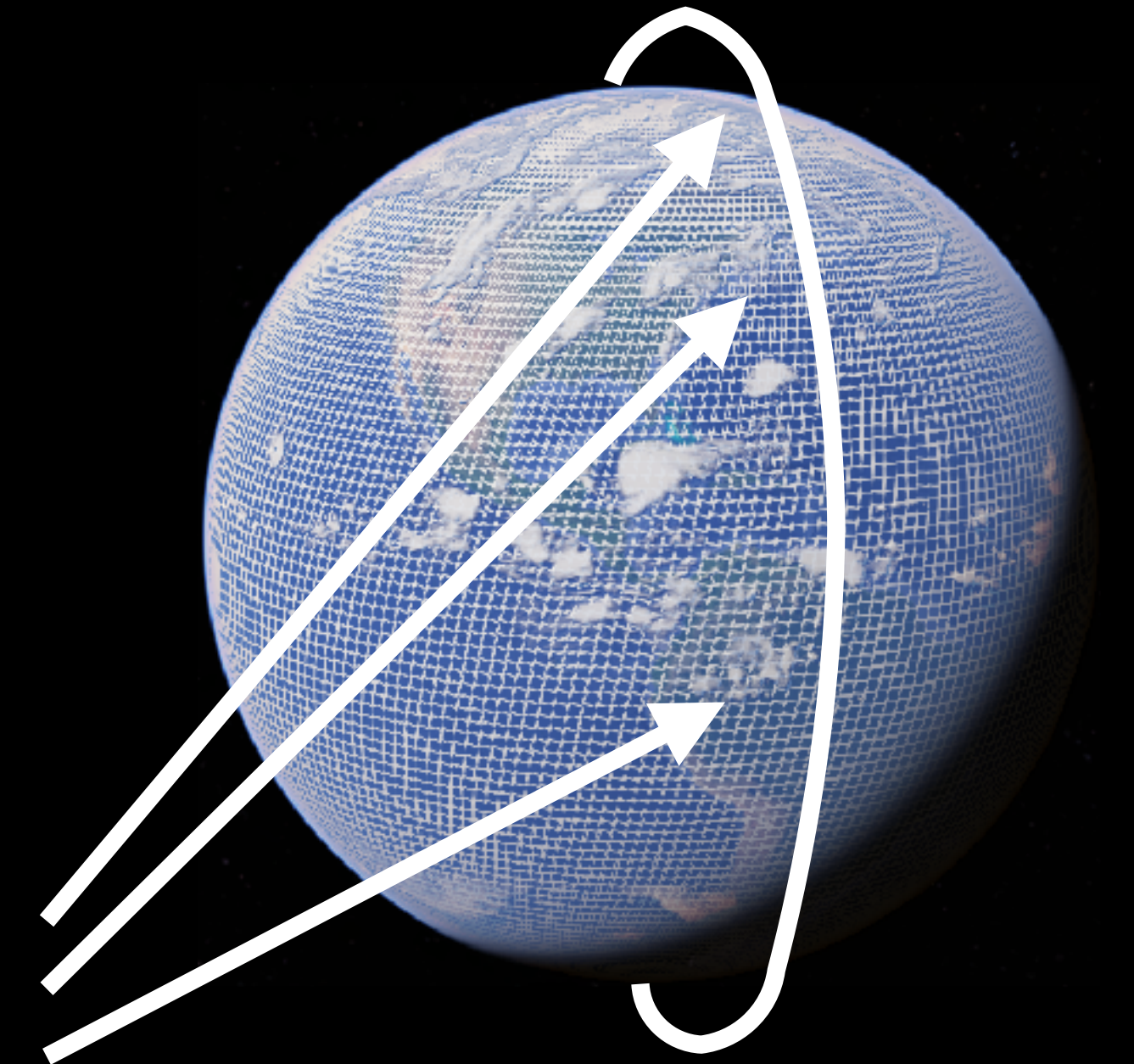
Communications Configuration

Simulator Outputs

Scenario Simulation



Event Traces

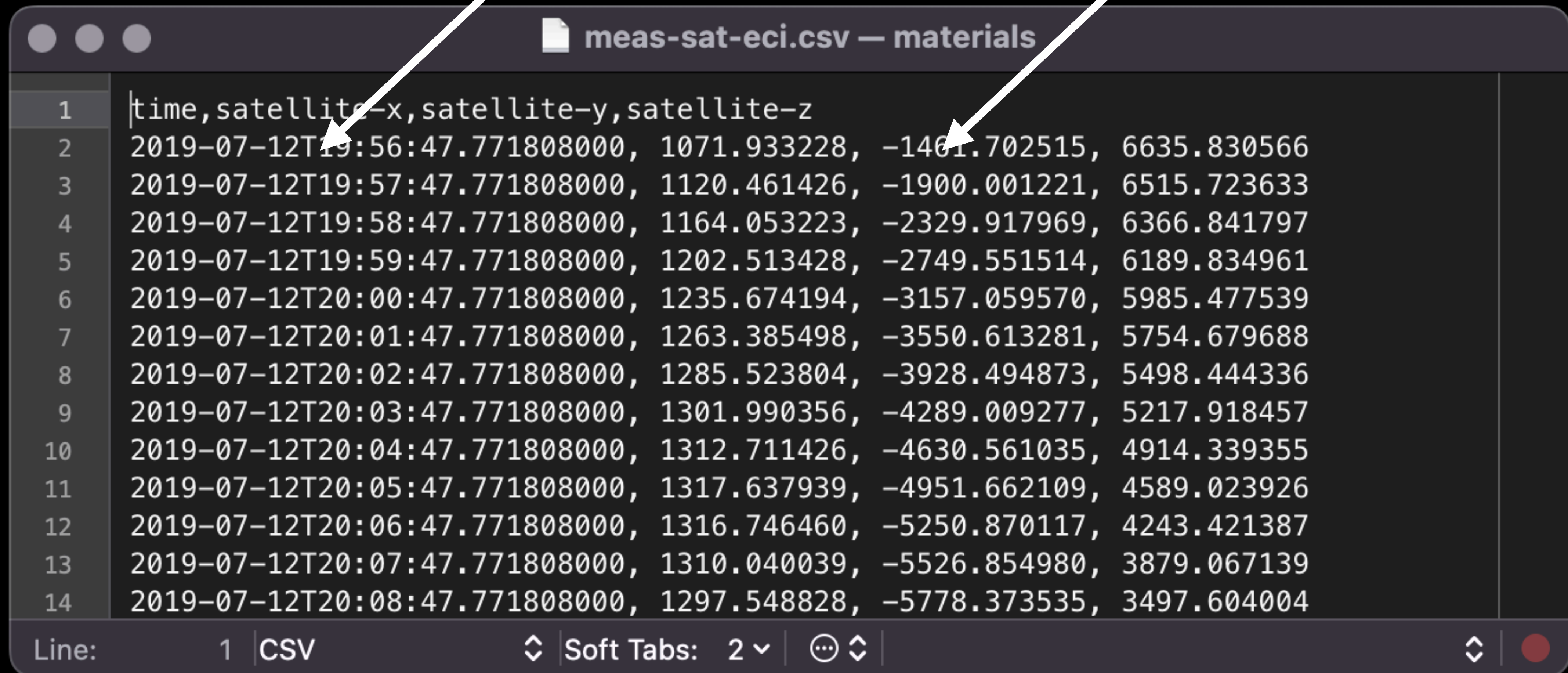


Observation Dates and Times
Satellite Activity Traces
Communication Logs

Example Output Log File

Log Date and Time

Satellite ECI Position



meas-sat-eci.csv — materials

	time,satellite-x,satellite-y,satellite-z
1	2019-07-12T19:56:47.771808000, 1071.933228, -1461.702515, 6635.830566
2	2019-07-12T19:57:47.771808000, 1120.461426, -1900.001221, 6515.723633
3	2019-07-12T19:58:47.771808000, 1164.053223, -2329.917969, 6366.841797
4	2019-07-12T19:59:47.771808000, 1202.513428, -2749.551514, 6189.834961
5	2019-07-12T20:00:47.771808000, 1235.674194, -3157.059570, 5985.477539
6	2019-07-12T20:01:47.771808000, 1263.385498, -3550.613281, 5754.679688
7	2019-07-12T20:02:47.771808000, 1285.523804, -3928.494873, 5498.444336
8	2019-07-12T20:03:47.771808000, 1301.990356, -4289.009277, 5217.918457
9	2019-07-12T20:04:47.771808000, 1312.711426, -4630.561035, 4914.339355
10	2019-07-12T20:05:47.771808000, 1317.637939, -4951.662109, 4589.023926
11	2019-07-12T20:06:47.771808000, 1316.746460, -5250.870117, 4243.421387
12	2019-07-12T20:07:47.771808000, 1310.040039, -5526.854980, 3879.067139
13	2019-07-12T20:08:47.771808000, 1297.548828, -5778.373535, 3497.604004
14	

Line: 1 CSV Soft Tabs: 2

Overview

Background and Related Work

Components of Space Simulation

The cote Workflow

Example Programs in cote

Open Source Development

<https://github.com/CMUAbstract/cote>



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Brad Denby Adds sample configuration files for capture and downlink example

3a3e4c9 on Jul 19 65 commits

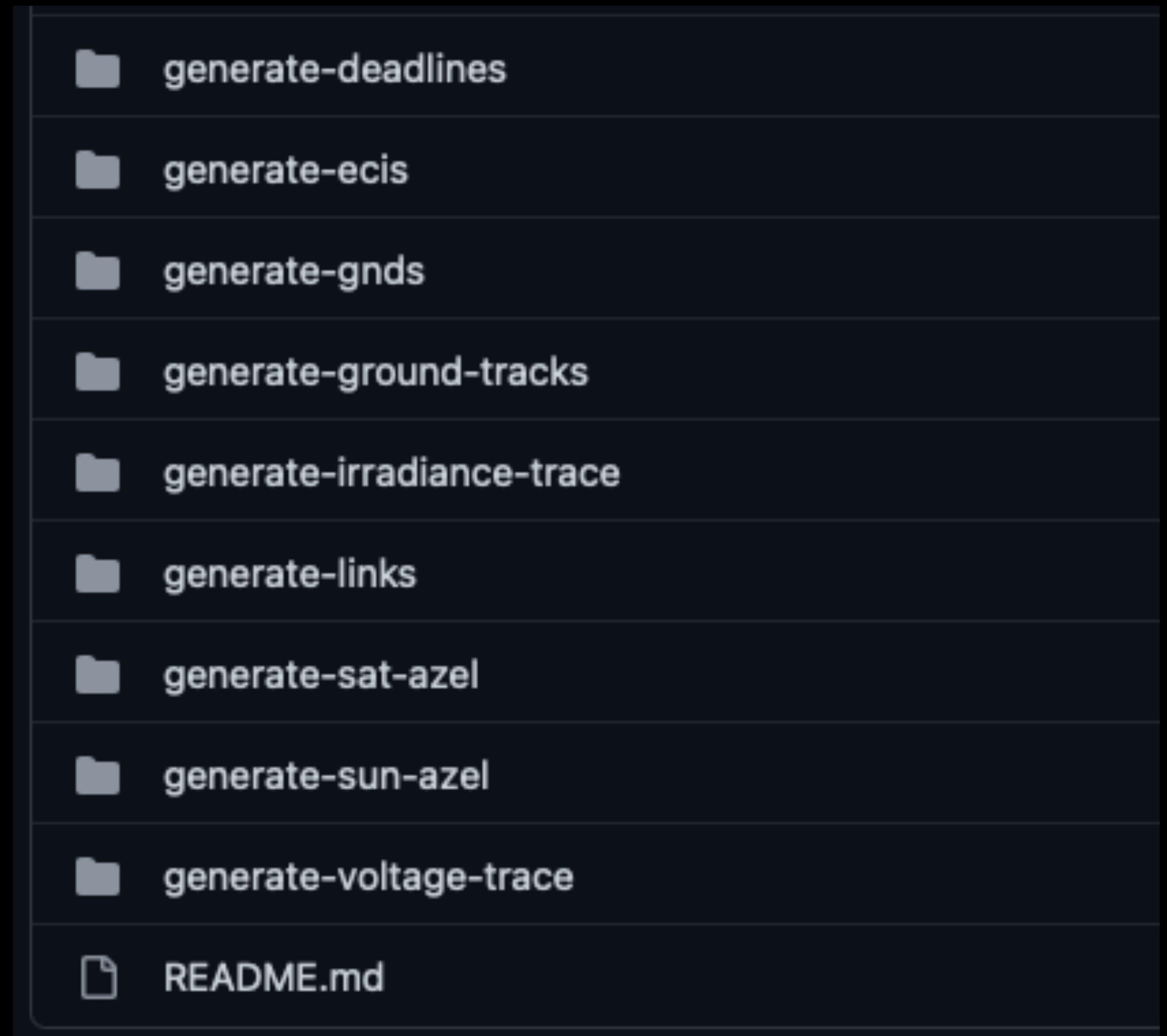
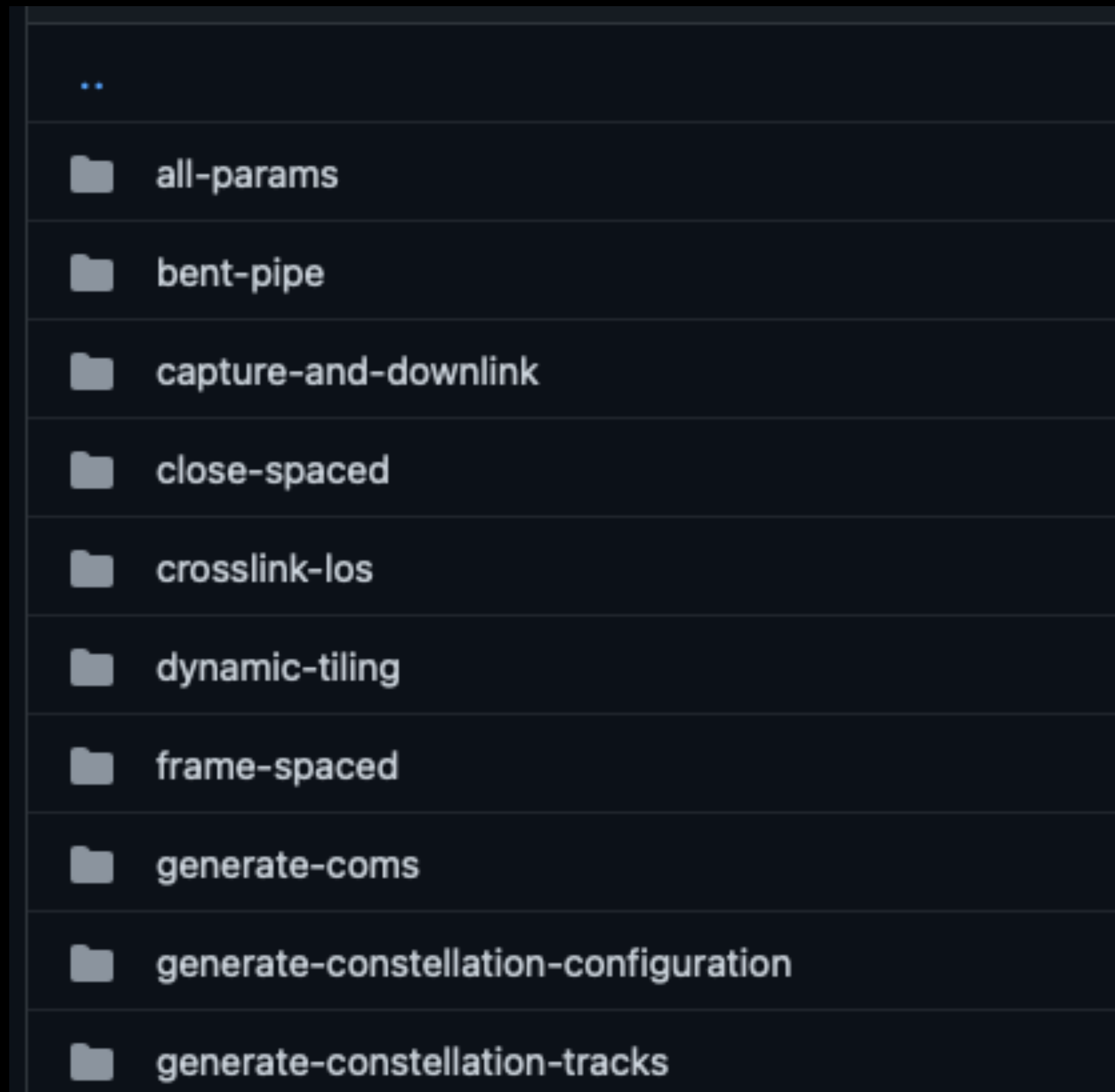
 analysis	Adds analysis scripts for all params satellite positions	2 years ago
 dependencies/parse-json-0.1.0	Adds all params parsing example	2 years ago
 examples	Adds sample configuration files for capture and downlink example	3 months ago
 images	cote v1.0.0 release	2 years ago
 references	cote v1.0.0 release	2 years ago
 scripts	Updates dependencies and prerequisites to avoid link rot	16 months ago
 software	Adds crosslink line-of-sight utility function	17 months ago

Orbital edge computing simulation software

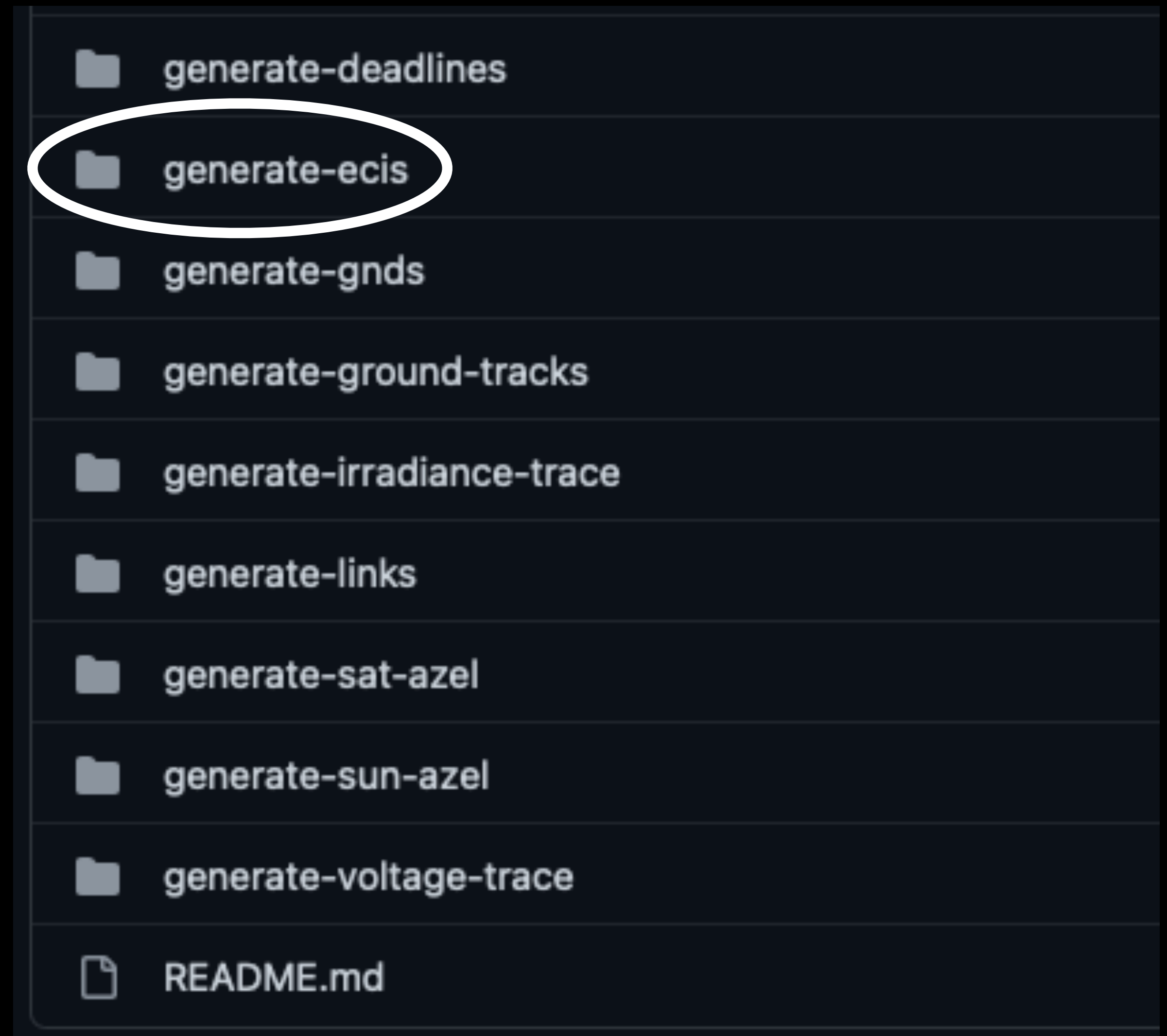
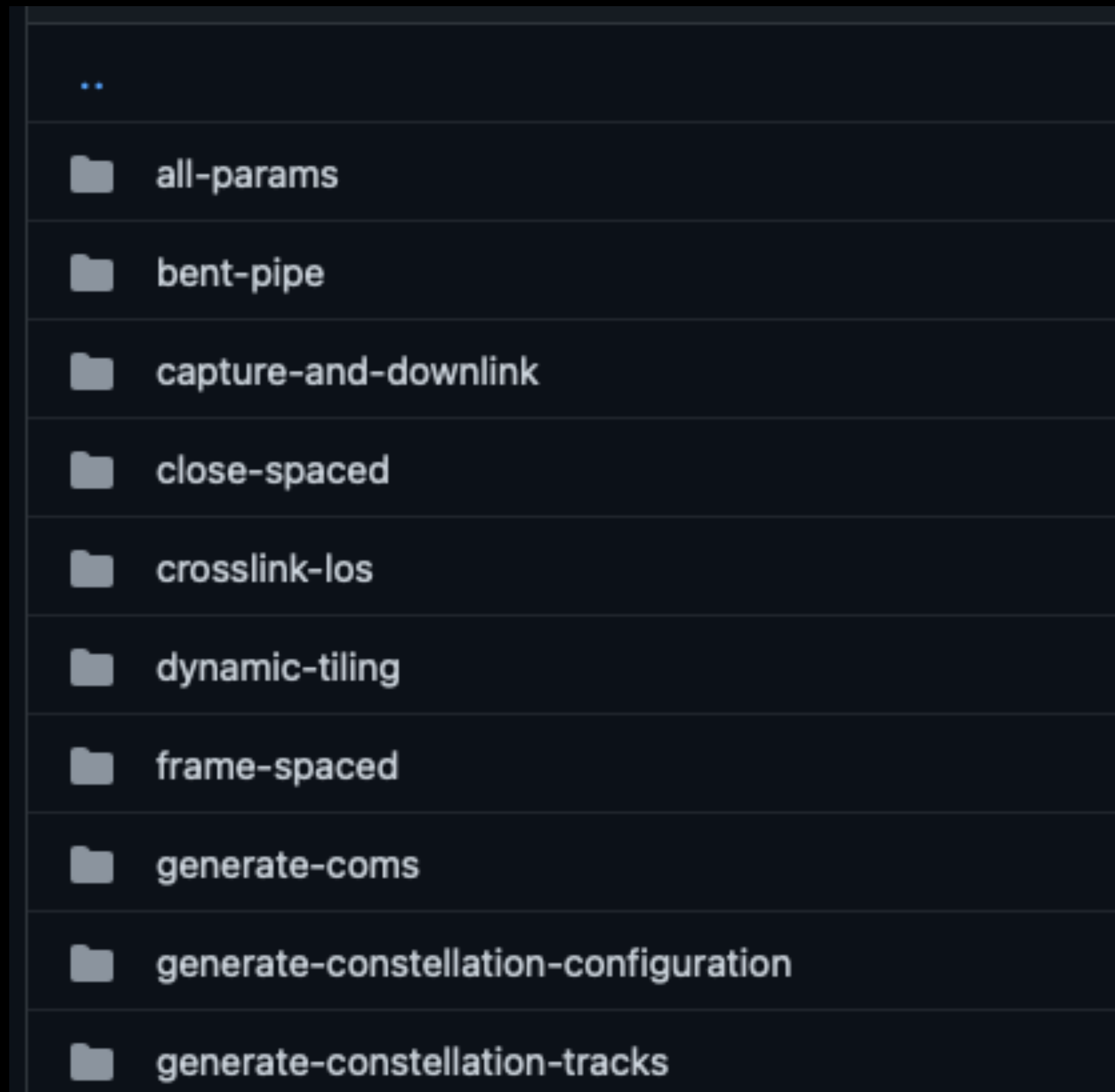
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Available Example Programs



Available Example Programs



Example Program: “Generate ECIs”

Input Configuration Files

Output Log Files

Example Program: “Generate ECIs”

Input Configuration Files

Output Log Files



Time Step: 1 minute

Example Program: “Generate ECIs”

Input Configuration Files

Output Log Files



Time Step: 1 minute



Step Count: 1440 (one day)

Example Program: “Generate ECIs”

Input Configuration Files

Output Log Files



Time Step: 1 minute



Step Count: 1440 (one day)



Simulation Start Date and Time

Example Program: “Generate ECIs”

Input Configuration Files

Output Log Files



Time Step: 1 minute



Step Count: 1440 (one day)



Simulation Start Date and Time



Satellite TLE

Example Program: “Generate ECIs”

Input Configuration Files



Time Step: 1 minute



Step Count: 1440 (one day)



Simulation Start Date and Time



Satellite TLE

Output Log Files



**Satellite ECI x-position
(Once per minute)**

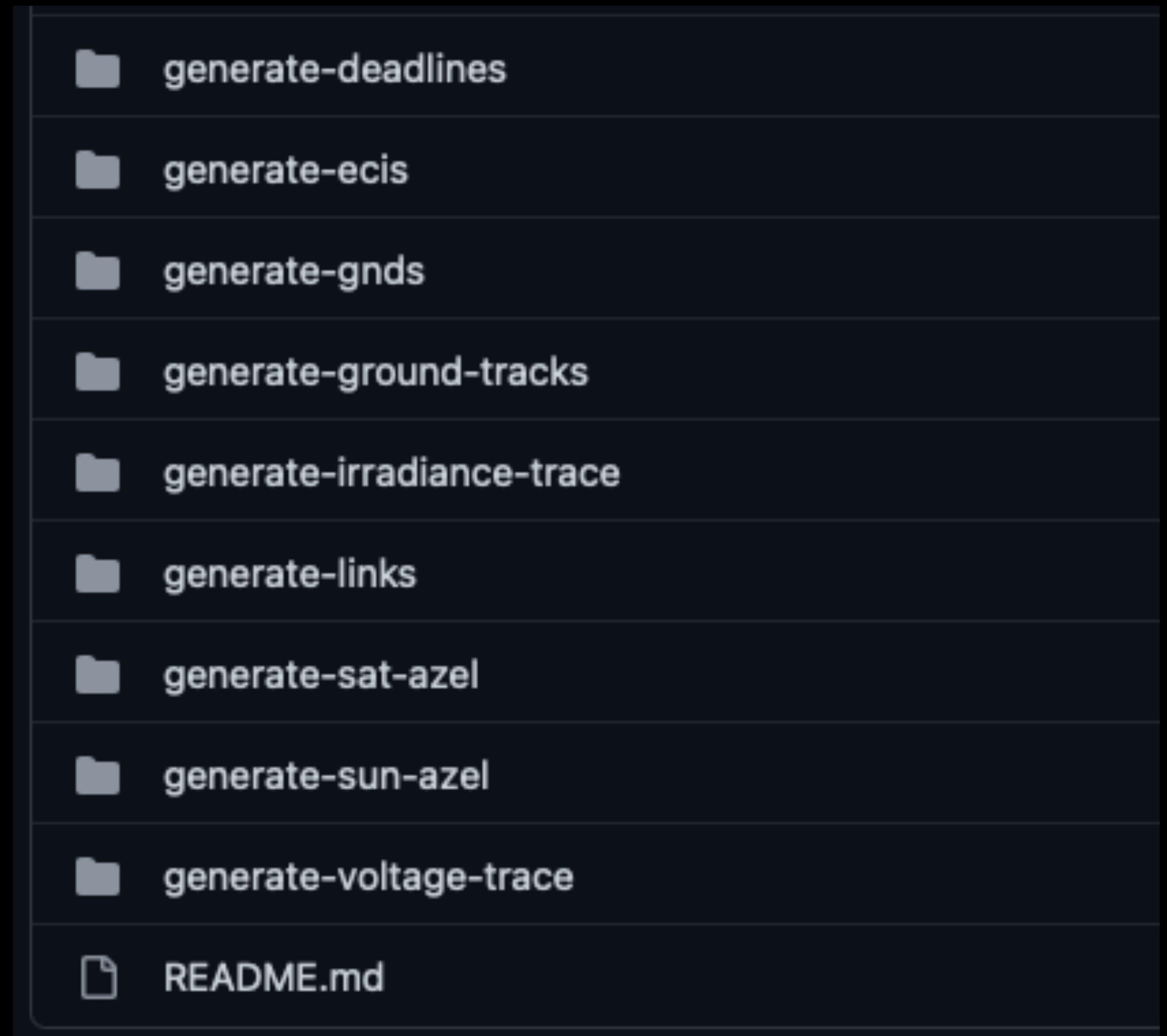
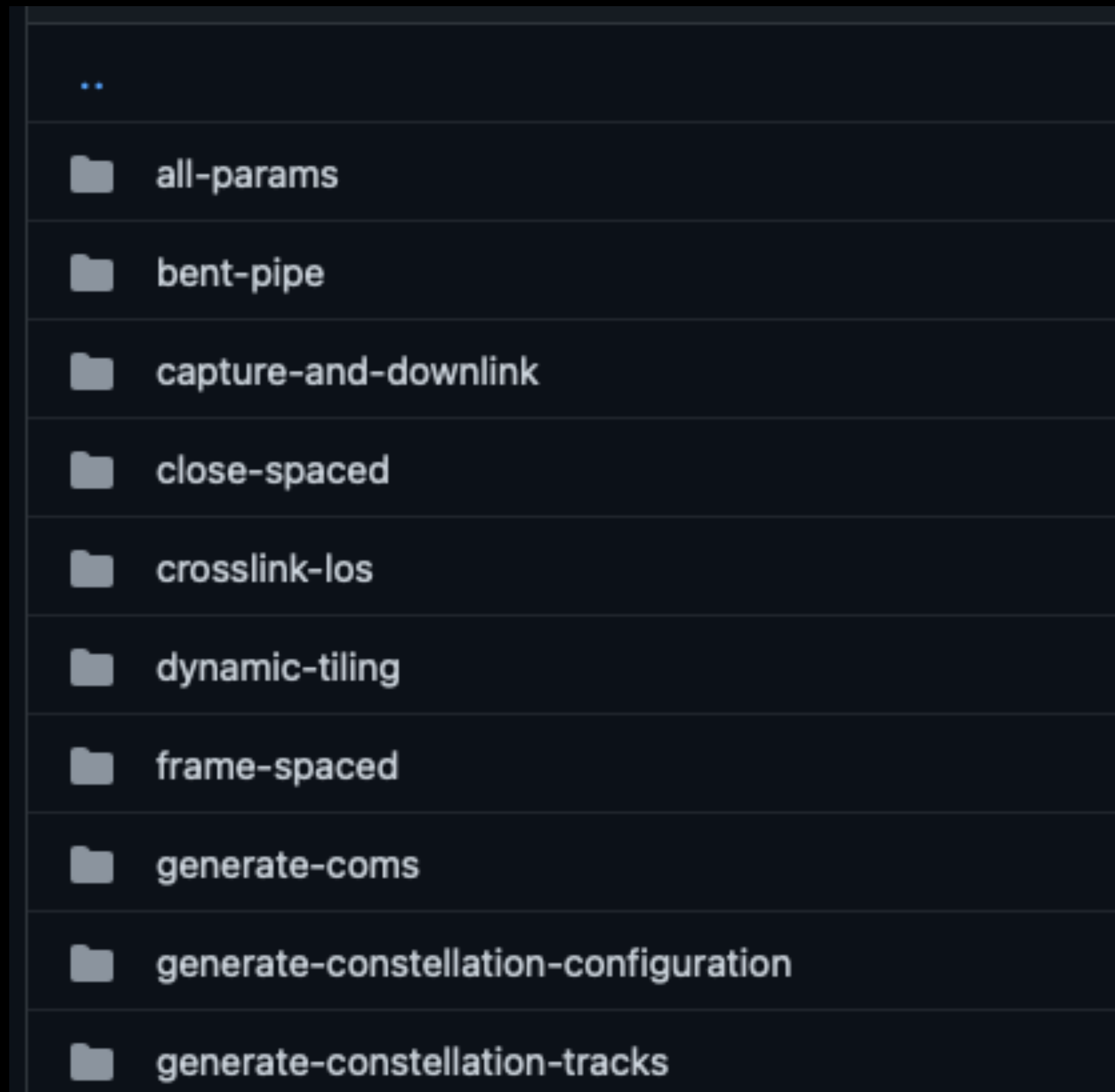


**Satellite ECI y-position
(Once per minute)**

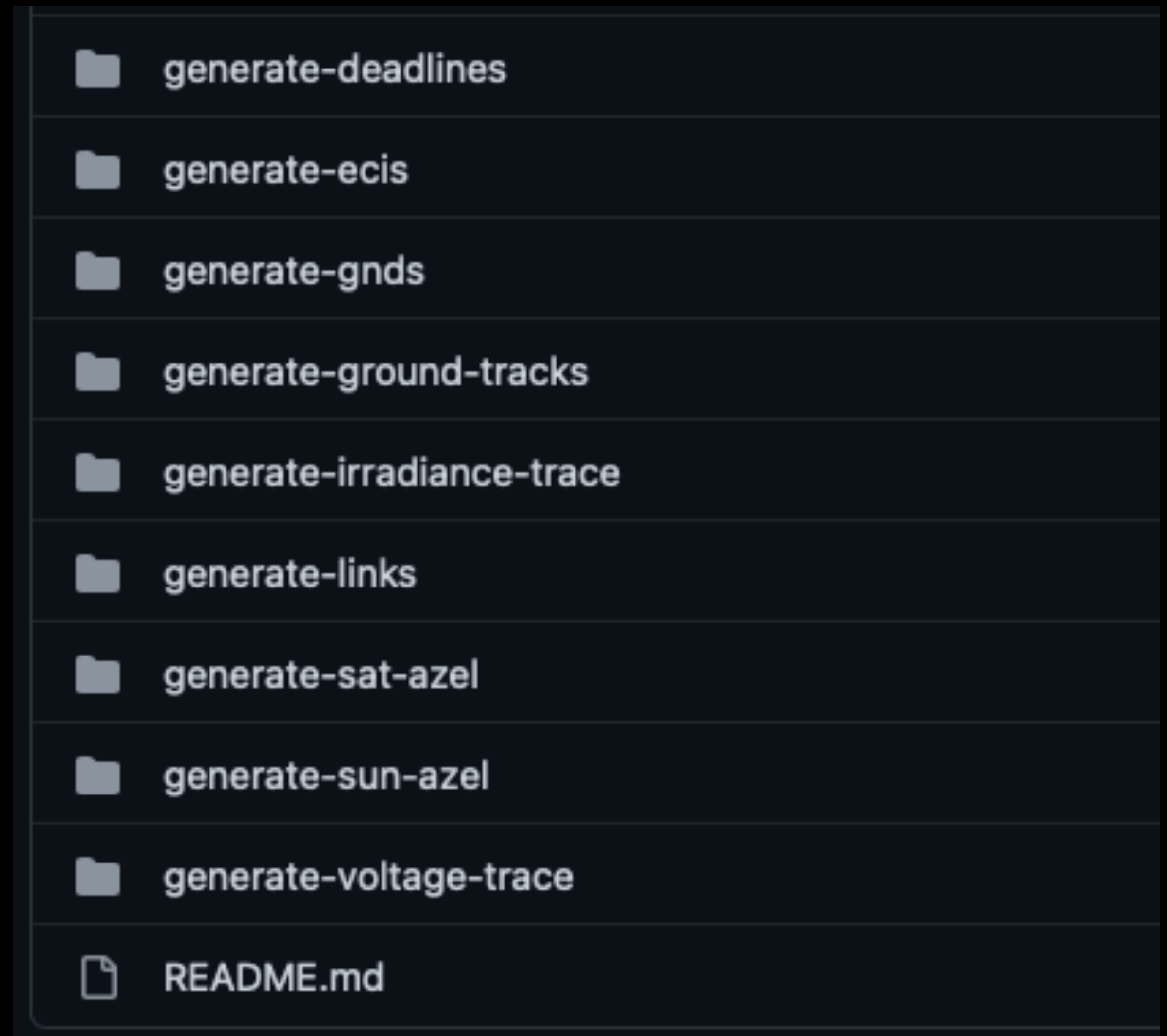
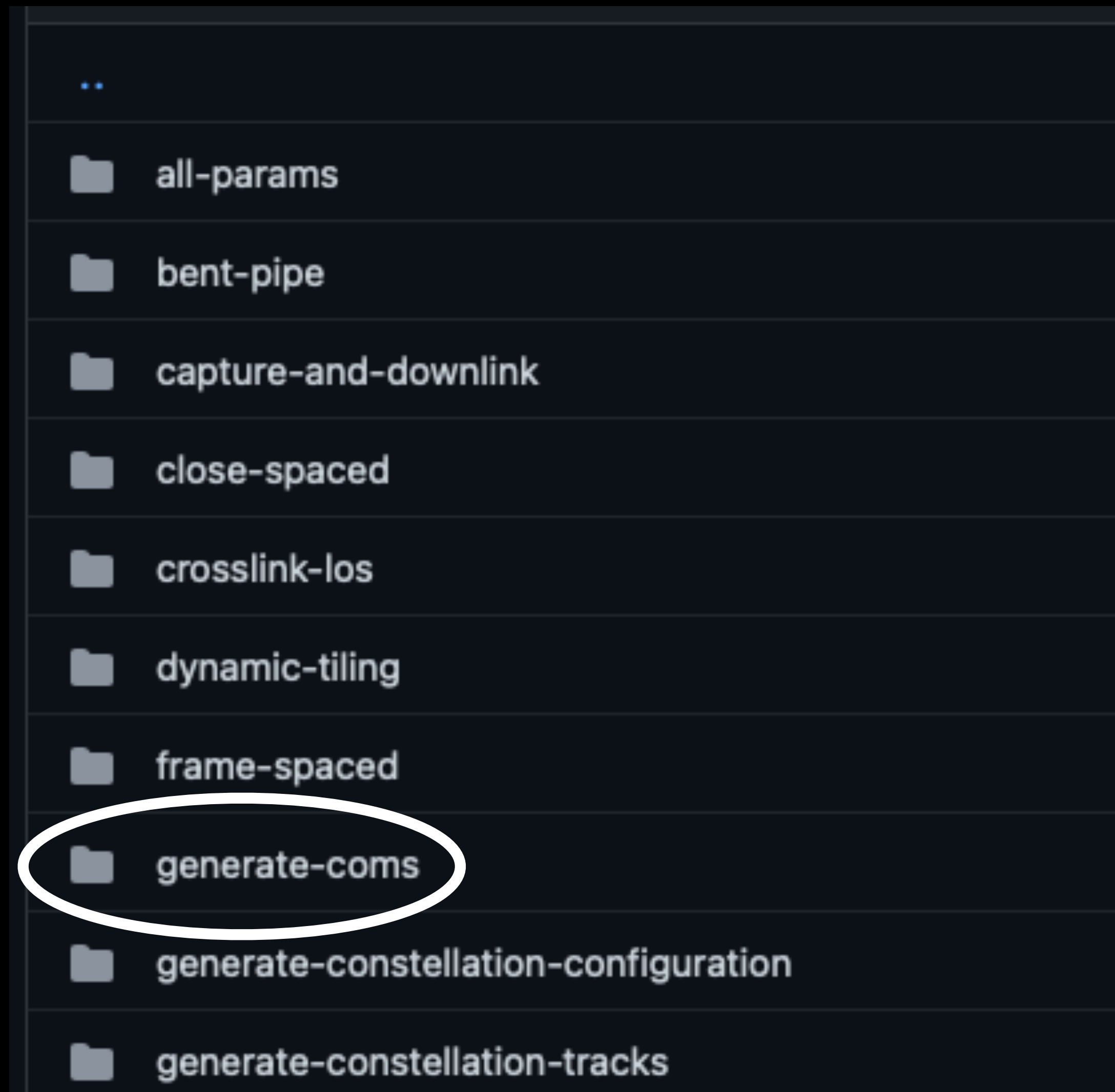


**Satellite ECI z-position
(Once per minute)**

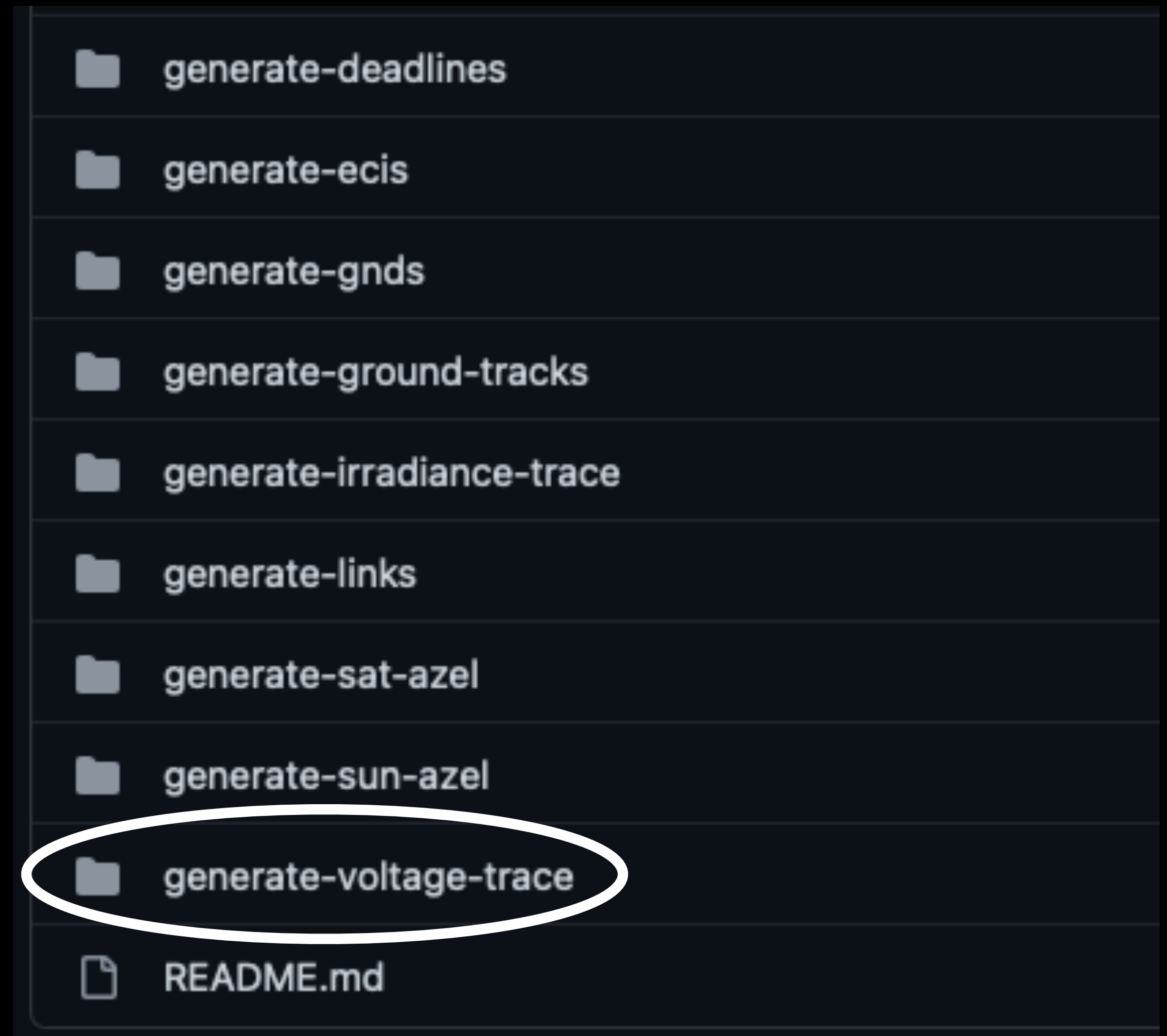
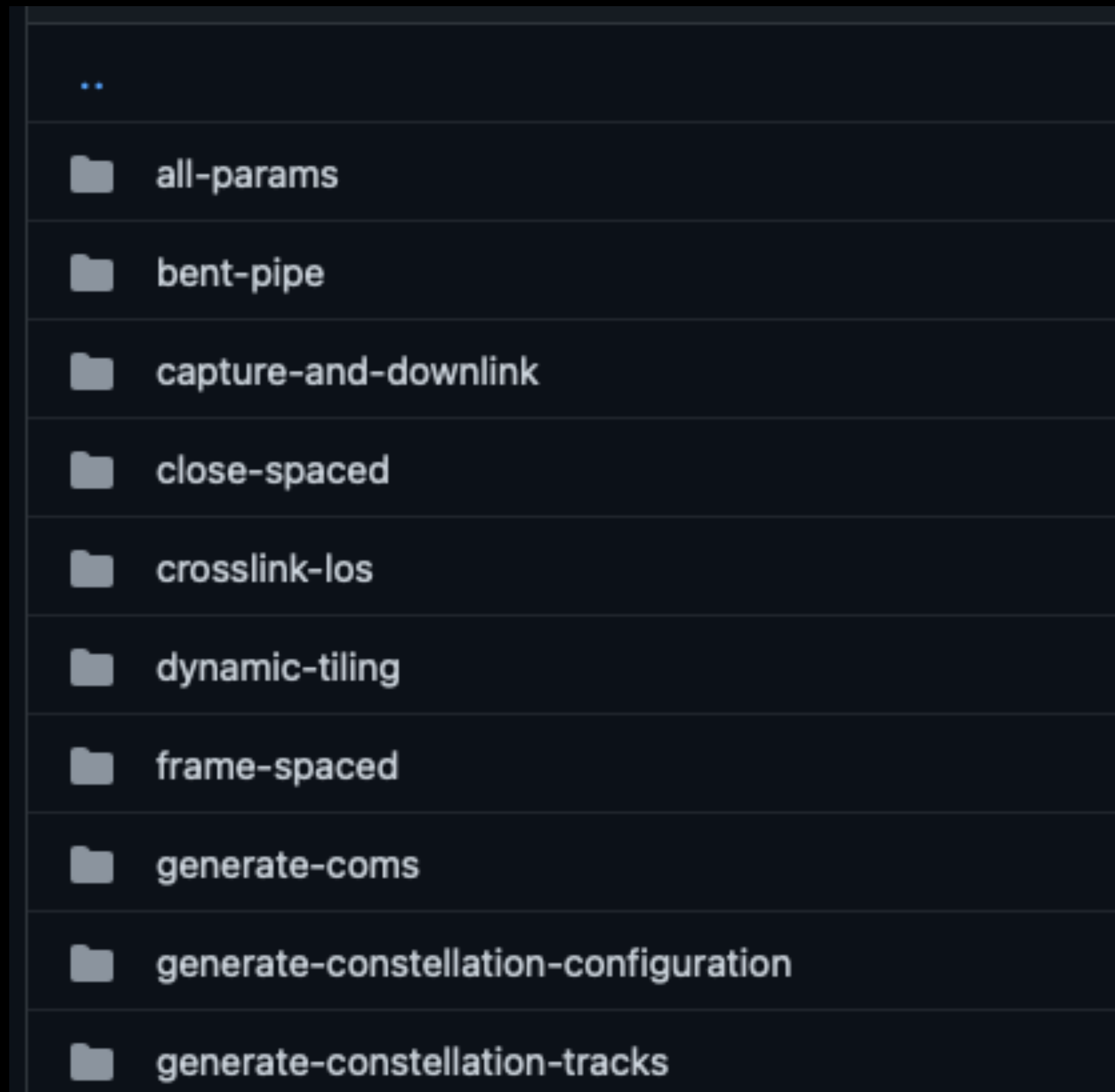
Available Example Programs



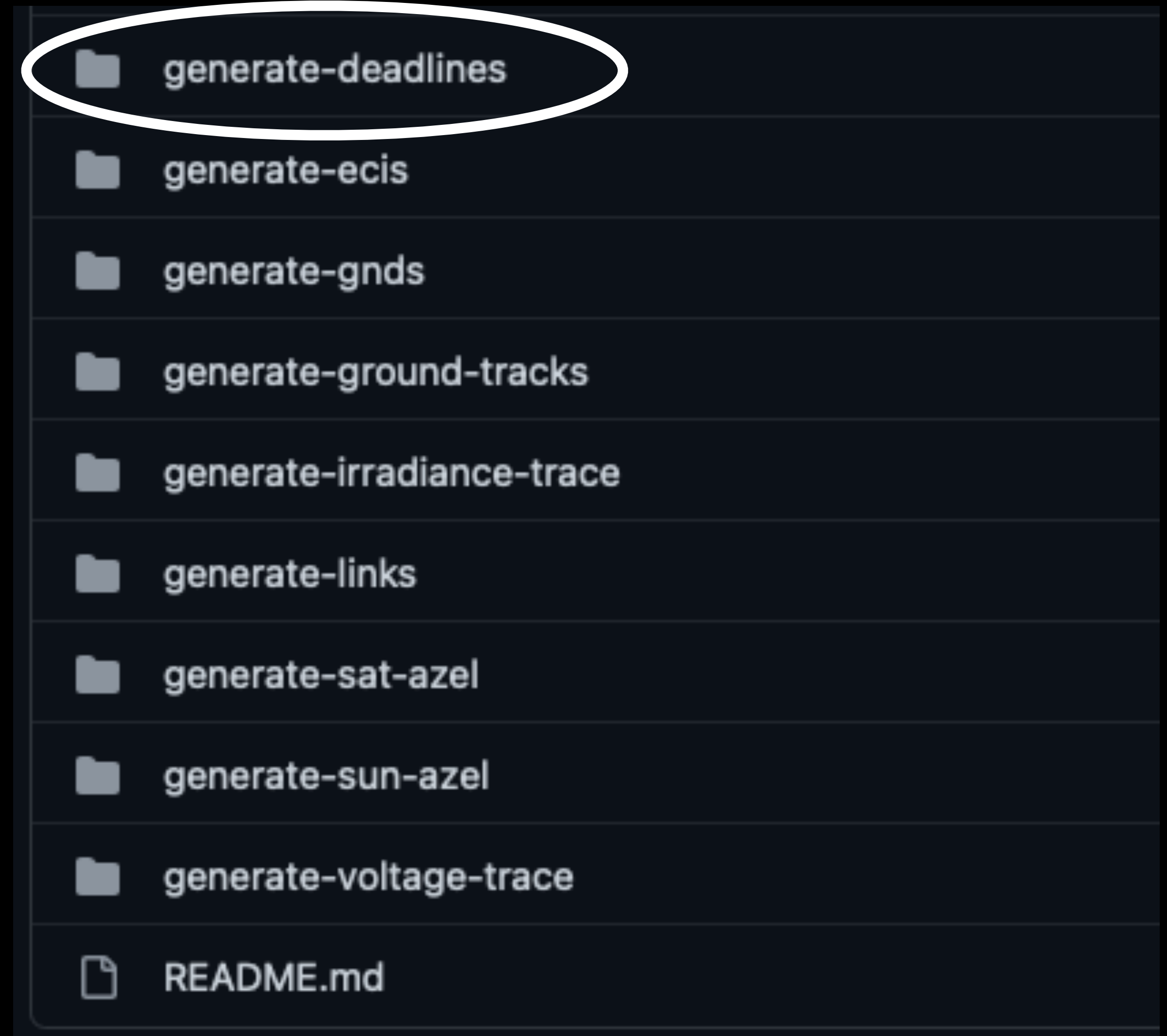
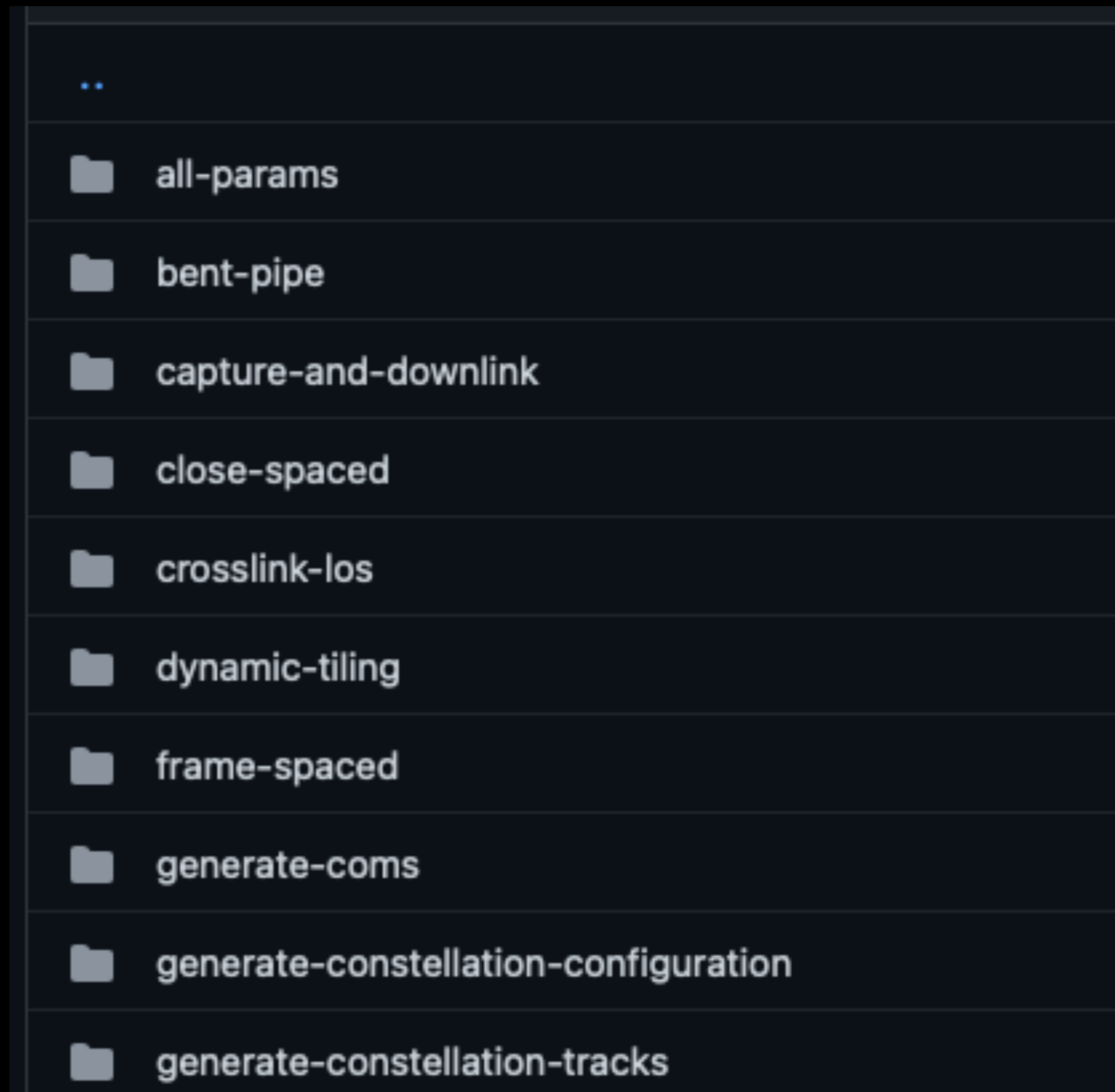
Available Example Programs



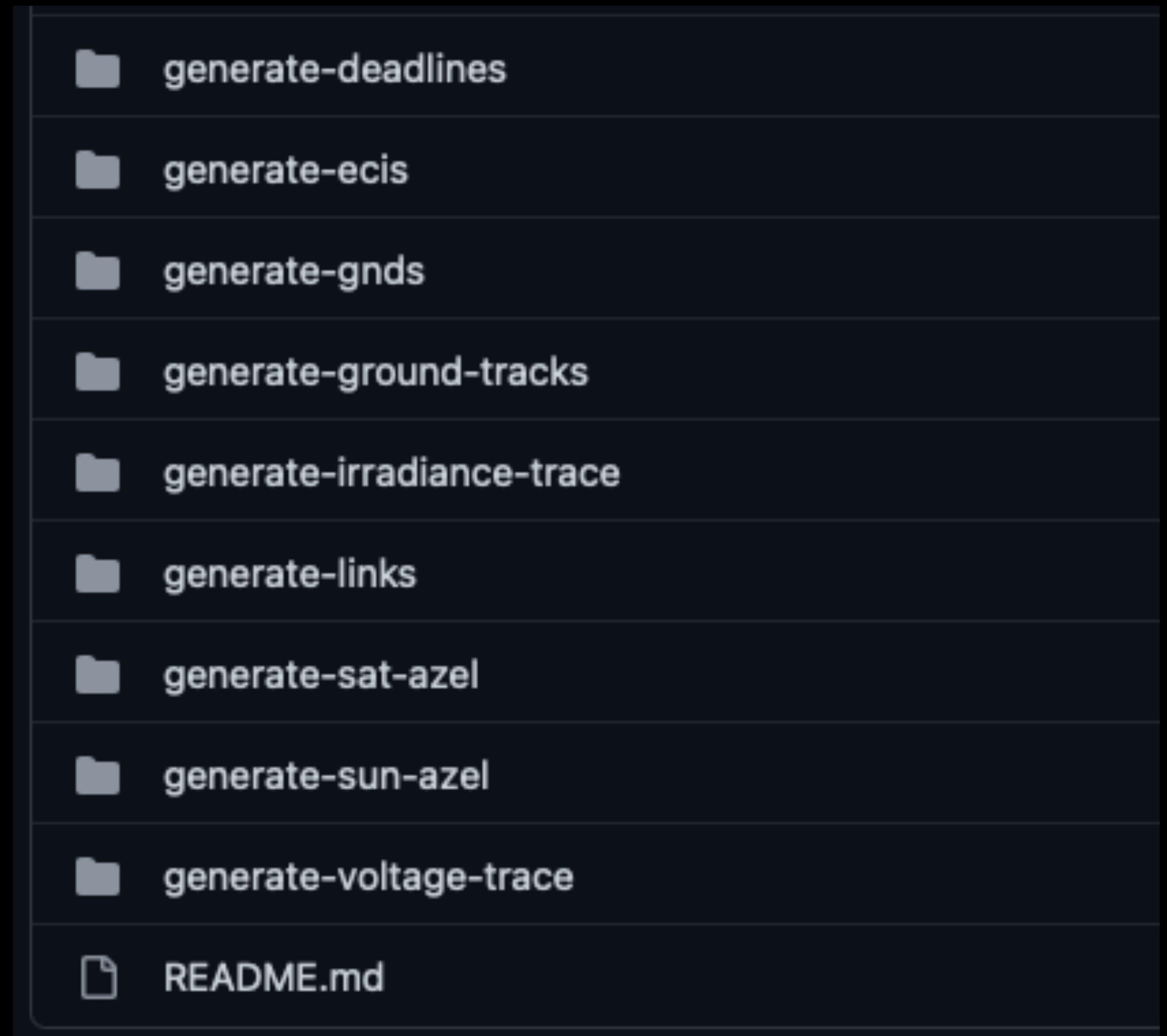
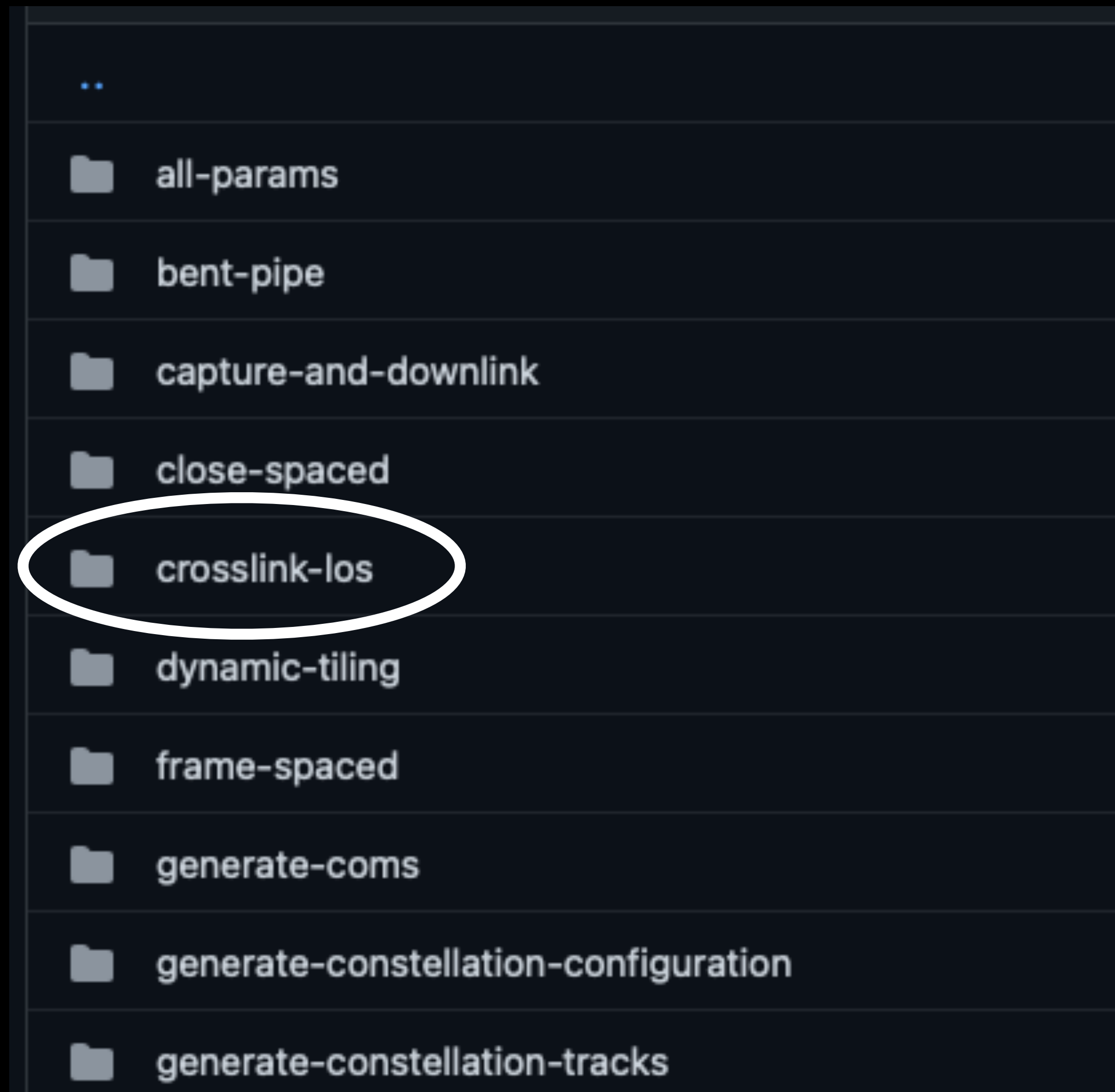
Available Example Programs



Available Example Programs



Available Example Programs



Example Program: “Crosslink L.O.S.”

Input Configuration Files

Output Log Files

Example Program: “Crosslink L.O.S.”

Input Configuration Files

Output Log Files



Time Step: 1 minute



Step Count: 49 (half orbit)



Simulation Start Date and Time



Many Satellite TLEs

Example Program: “Crosslink L.O.S.”

Input Configuration Files



Time Step: 1 minute



Step Count: 49 (half orbit)



Simulation Start Date and Time



Many Satellite TLEs

Output Log Files



Per-satellite link destination

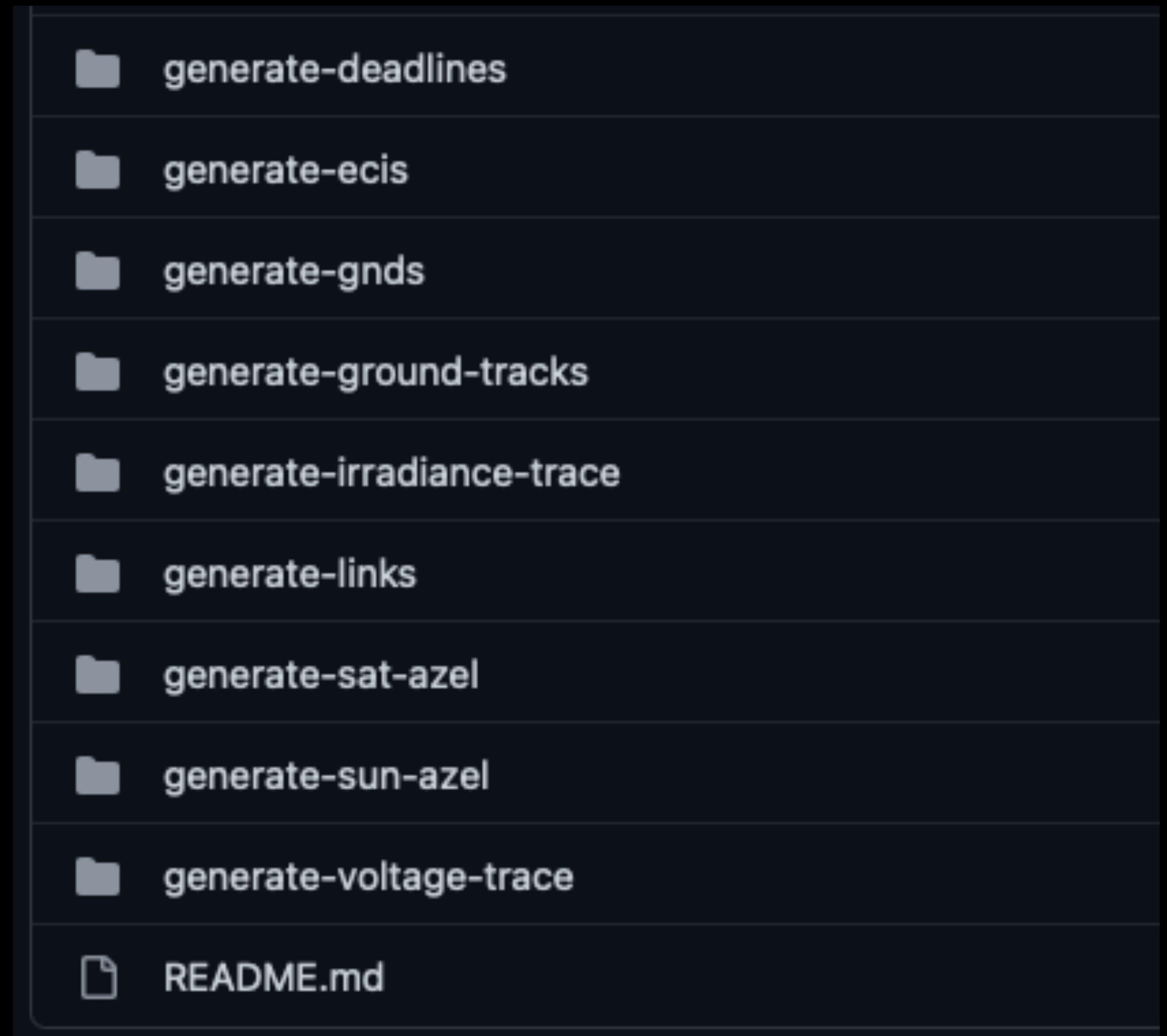
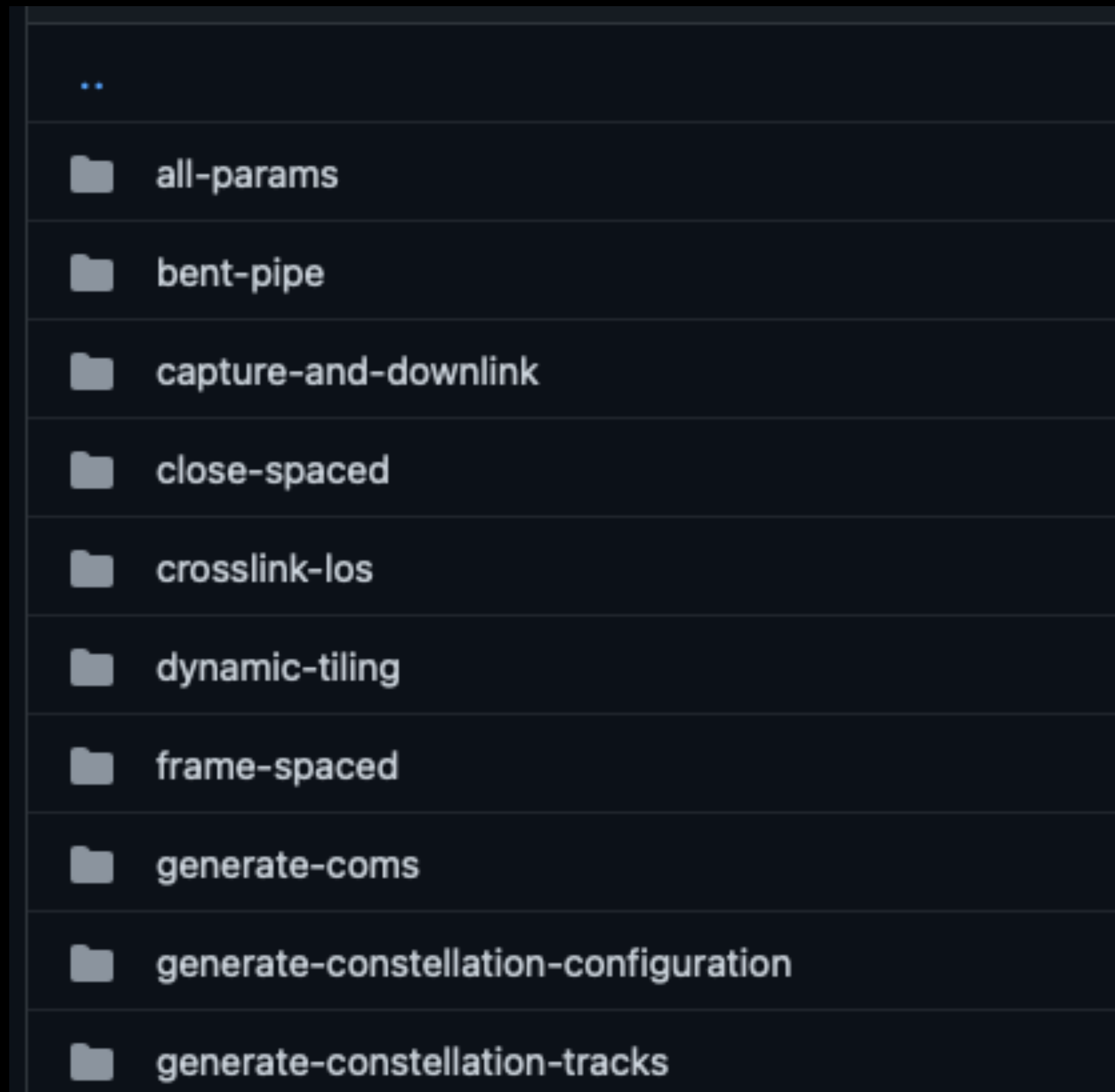


Per-satellite link distance

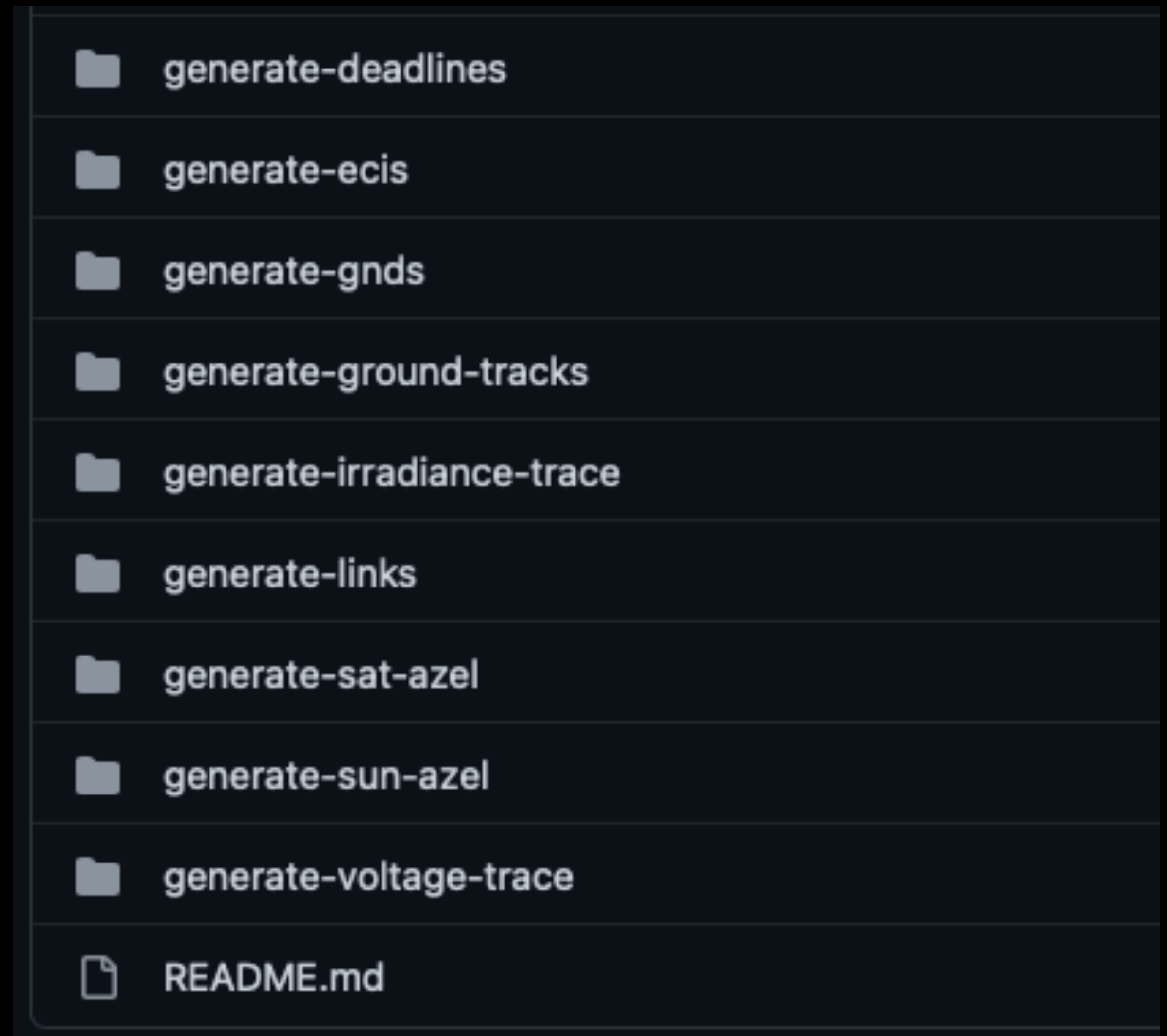
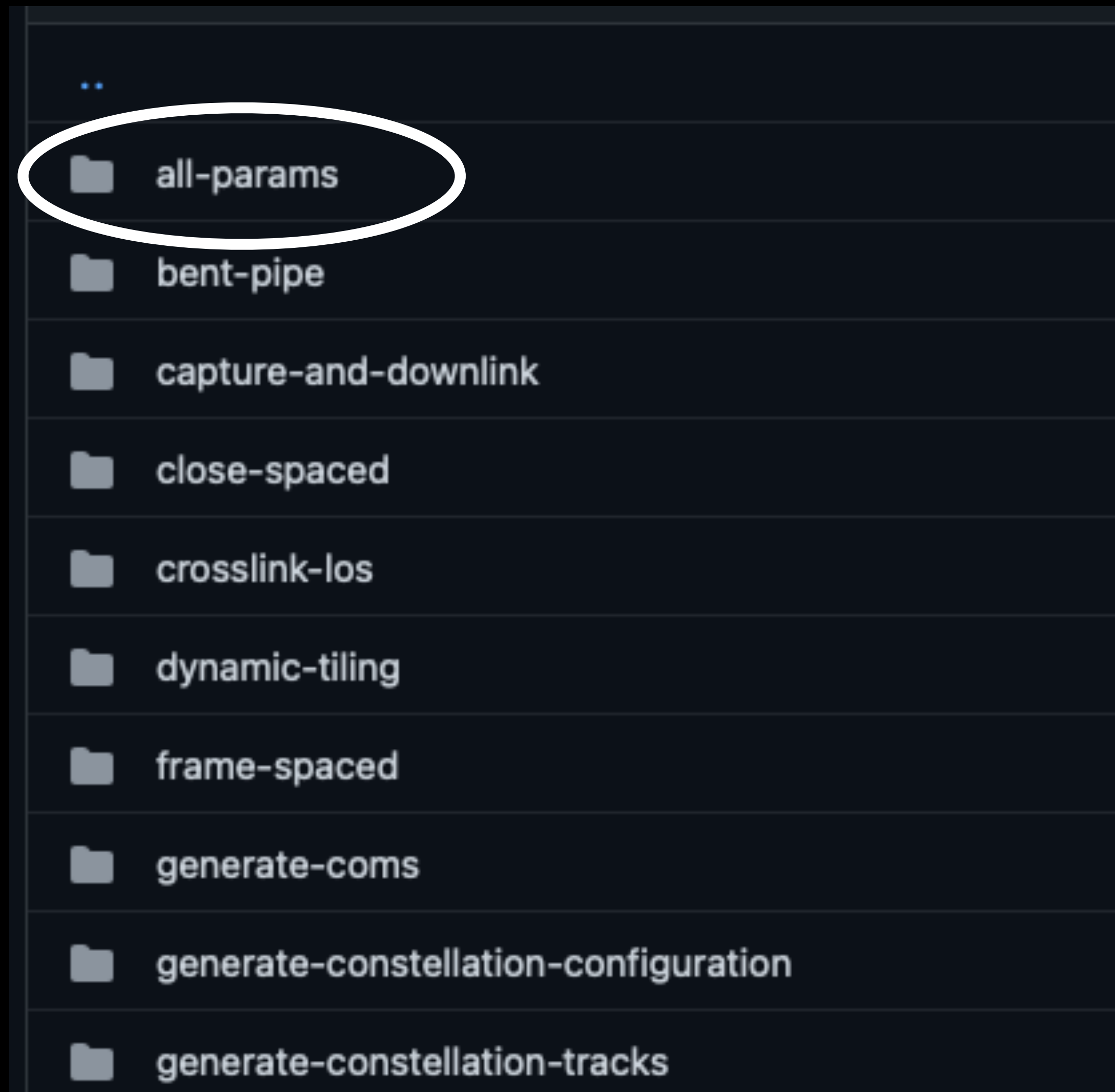


Per-satellite ECI positions (x, y, and z)

Available Example Programs



Available Example Programs



Open Source Development

<https://github.com/CMUAbstract/cote>



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Background and Related Work

Components of Space Simulation

The cote Workflow

Example Programs in cote

A satellite view of Earth from space, showing a portion of the African continent and surrounding oceans. The text is overlaid on the left side of the image.

cote

Software Simulation of the Space Environment

Brad Denby, bdenby@cmu.edu

Advisor: Brandon Lucia, blucia@andrew.cmu.edu

<https://github.com/CMUAbstract/cote>

Carnegie Mellon University