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NUCLEAR ENGINEERING
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Nanoracks

Multi-modal Surveillance of Localized Processes Using Cube Satellite Platforms: Phenomena, Signatures, and Feasible Architectures

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ETI

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National Nuclear Security Administration

Overview

- Introduction
- Phenomena and Signatures
- CubeSat Platform Analysis
- Orbital Modelling
- Conclusions and Future Work

Introduction

Cube satellites (CubeSats) provide a unique platform for monitoring localized processes anywhere within the Earth's surface or atmospheric levels in regards to nuclear security.

- Areas of interest can be targeted at certain times on an on-demand basis
- CubeSats equipped with adequate sensors and data analytics capabilities can create a characterization surveillance method for phenomena on interest
- Advantageous over conventional satellites because of cost and simplicity

Timeline

The effort is focused on science and technology of predictive and on-demand characterization of localized developments on the earth surface, subsurface and within atmosphere:

*Task 1: CubeSat-based global surveyor architecture development

*Task 2: Specification development for a CubeSat-based global surveyor

Task 3. Computational and experimental program based on surrogate and simulated data sets demonstrating capabilities of the orbital surveyor platform

Task 4. CubeSat design and data analysis towards a future demonstration launch program

Schedule:

Year 1: CubeSat-based global surveyor architecture development
Year 2: Specification development for a CubeSat-based global surveyor
Year 3: Computational and experimental program based on surrogate and simulated data sets demonstrating capabilities of the proposed orbital surveyor platform
Year 4: CubeSat design and data analysis towards a future demonstration launch program
Year 5: Continuation of all work

Task 1: CubeSat-based global surveyor architecture development

1.1. CubeSat configuration and platform capabilities

1.2. Instrumentation options analysis for CubeSat based surface and atmospheric surveys

1.3. Enabling data analysis methods to support data fusion, reconstruction, and predictive analysis

1.4. Multi-modal signature development accounting for high resolution remote sensing data streams

1.5. Prototype concept and computational analysis to demonstrate capability

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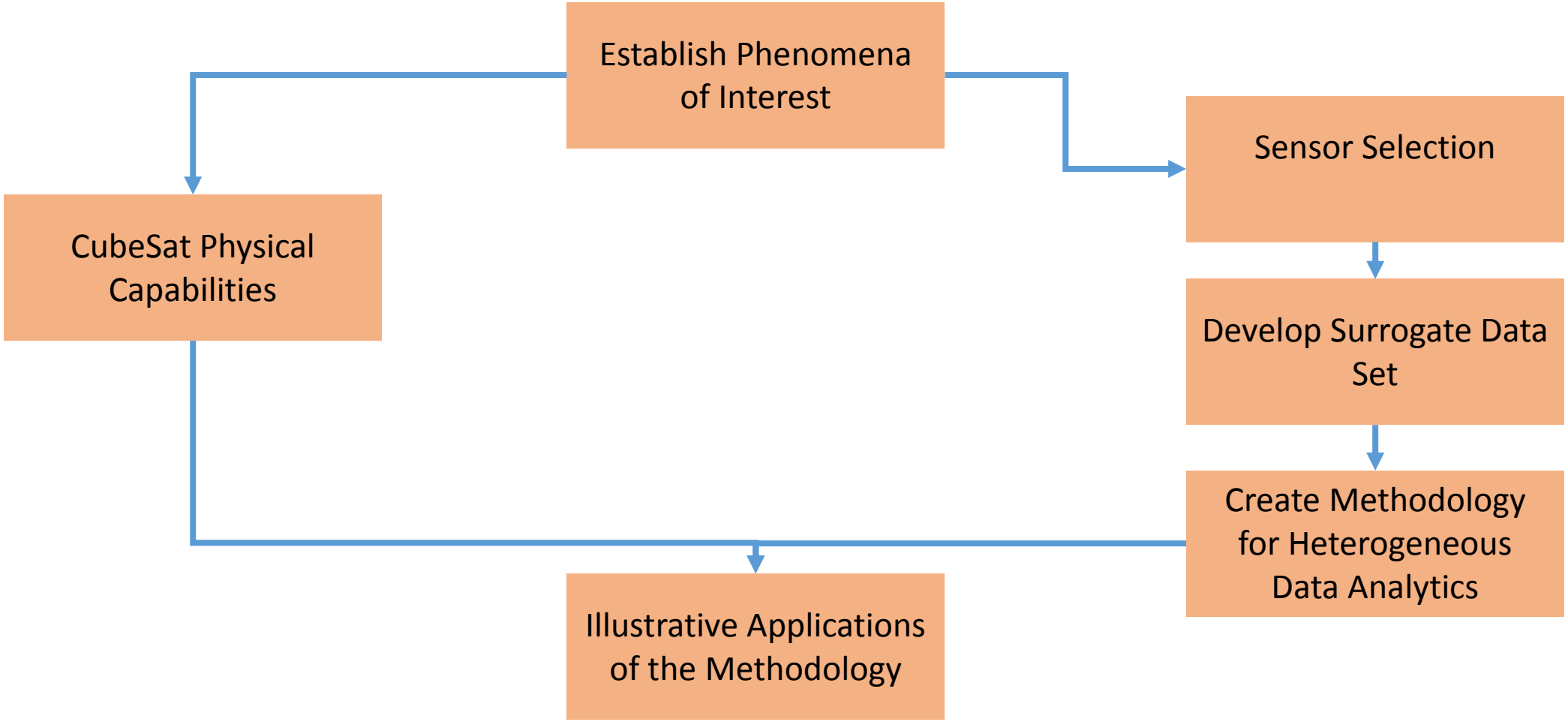
Task 2: Specification development for a CubeSat-based global surveyor

2.1. CubeSat very high-resolution sensing options with focus on optical image analysis, reconstruction and signature development

2.2. Multi-modal spectral signature analysis options in CubeSat architectures

2.3. Hardware specification development and integration options analysis

CubeSat-based Surveillance Platform Development



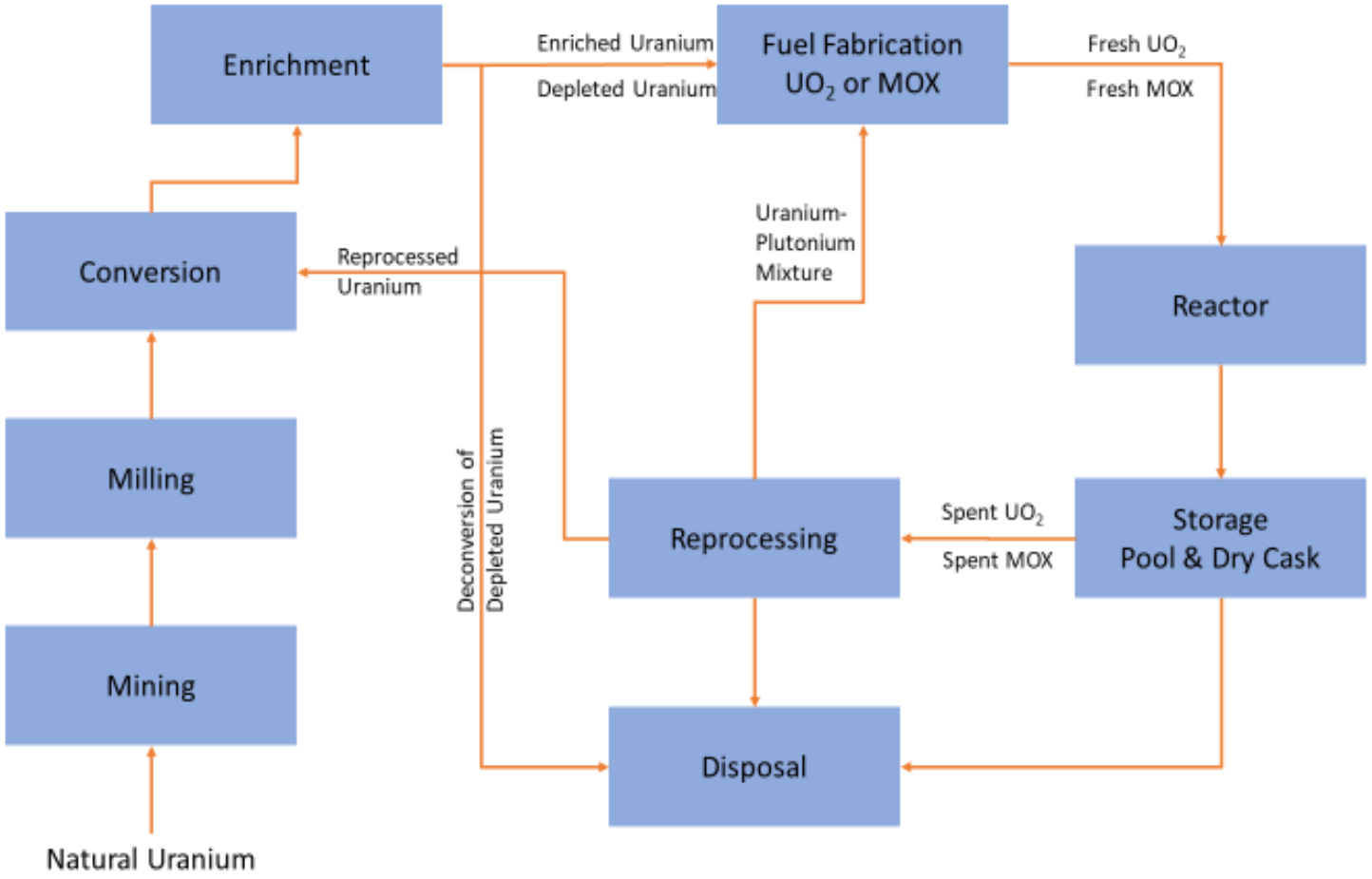
Phenomena and Signatures

Phenomena and Signatures

- First step in developing a CubeSat-based surveillance system
- Types of phenomena of interest for observation will determine CubeSat physical architecture and sensors
- Due to life-time of CubeSats in orbit, the surveillance system is best suited for events of immediate interest on an on-demand and short-term periodic basis

Phenomena of Interest for Nuclear Security

- Vehicles of Interest
  - Automobiles and Airplanes
- Infrastructural Emergencies of Interest
  - Blackouts and Fires
- Construction and Mining Events of Interest

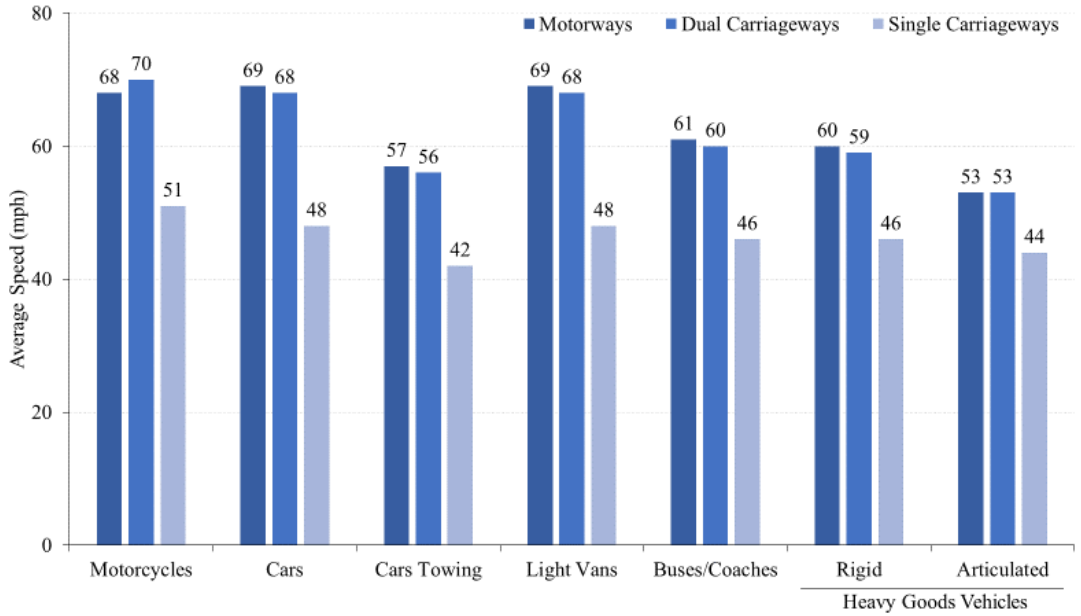


Characteristic Elements incorporated into the Signature Data Strings for Objects of Interest

- Dimensions
- Speed
- Emissions
- Temperatures
- Other

Dimension	Value
Height	1.414 m – 2.115 m
Length	2.695 m – 5.399 m
Width	1.475 m – 2.070 m

Minimum and Maximum Dimensions for all new vehicles sold in Europe[1]



Average vehicle speeds on highways in Great Britain in 2012[2]

Automobile Emissions[3]
CO_2
CH_4
CO
N_2O

Average Operating Temperature of Automobiles[4]
90-105 °C

Signatures for Infrastructural Emergencies of Interest

- Infrastructural Fires
  - Temperatures, Emissions, Aerosol Indices
- Blackouts
  - Temperatures, Light Indices

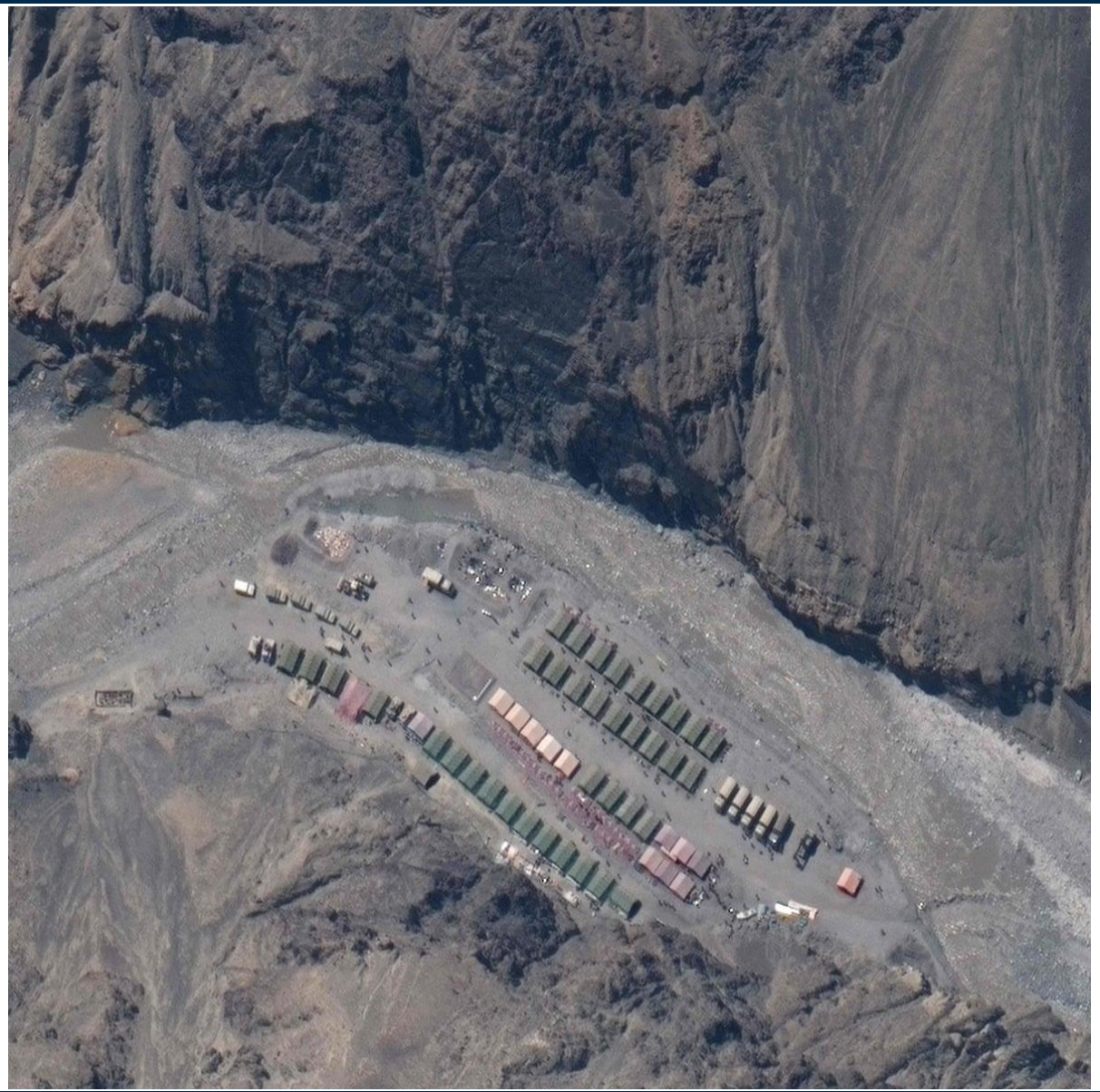
Type of Fire/Heat Source	Average Temperature
Infrastructural Fire[5,6]	350-1200 °C
Wildfire[7]	800 °C
Volcanic Plumes and Lava Flow[8]	600-1200 °C

Infrastructural Fire Emissions[9]
CO_2
CH_4
NO_x
Other materials inside

Signatures for Construction and Mining Events of Interest

- Construction
  - Vehicles
    - Same parameters as Vehicles of Interest
  - Temperatures, Emissions, Presence of Human Workers
- Mining
  - Vehicles
    - Same parameters as Vehicles of Interest
  - Temperatures, Emissions, Presence of Human Workers
  - Presence of Blasting Agents, Mine Footprint

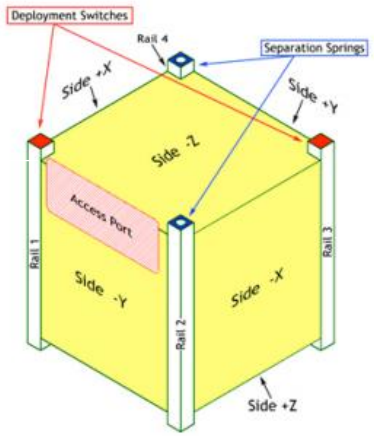
“Satellite images show Chinese construction near site of Indian border clash”[10]

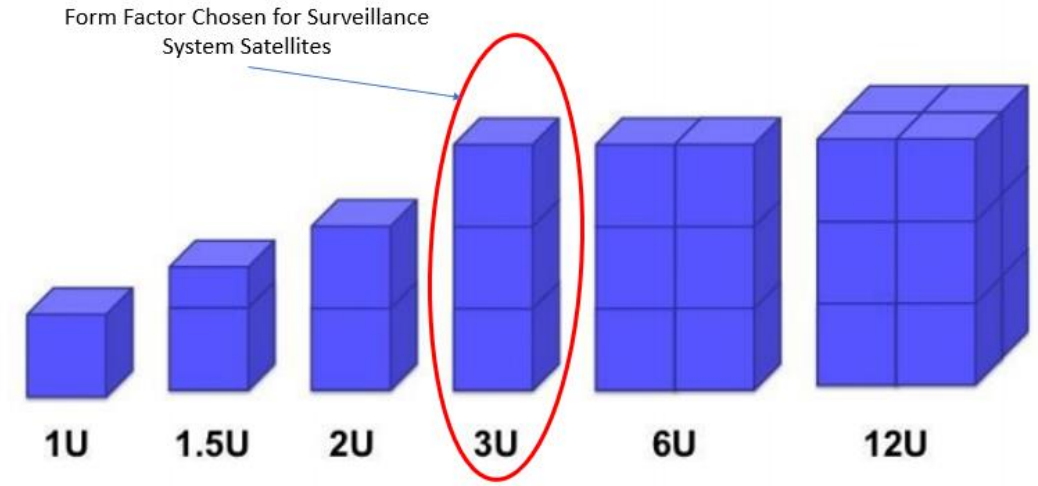


CubeSat Platform Analysis

CubeSat Architecture

- CubeSats are measured in units of U, 1U is equal to 10 cm x 10 cm x 10 cm cube with a mass close to 1 kg
- Sizes range from 1U to 12U
- Most common and versatile form factor: 3U
- Allows for the use of COTS components

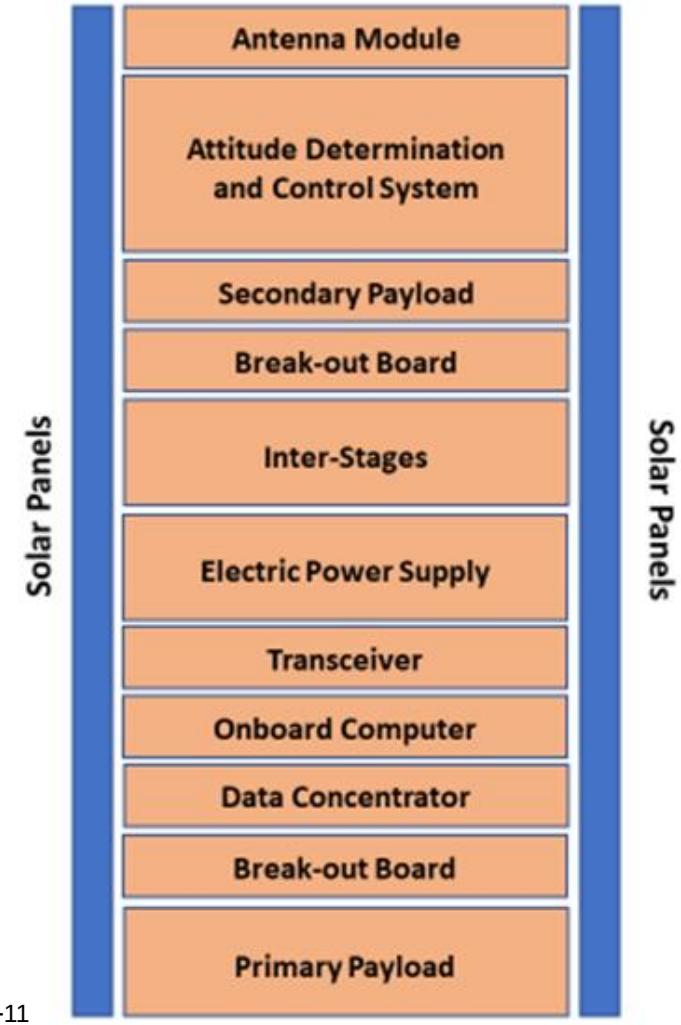




Major CubeSat Components

- Payload (Sensor)
- Power Supply
- Transceiver
- Solar Panels
- Attitude Control System
- Antennas
- Onboard Computer and Circuitry

COTS



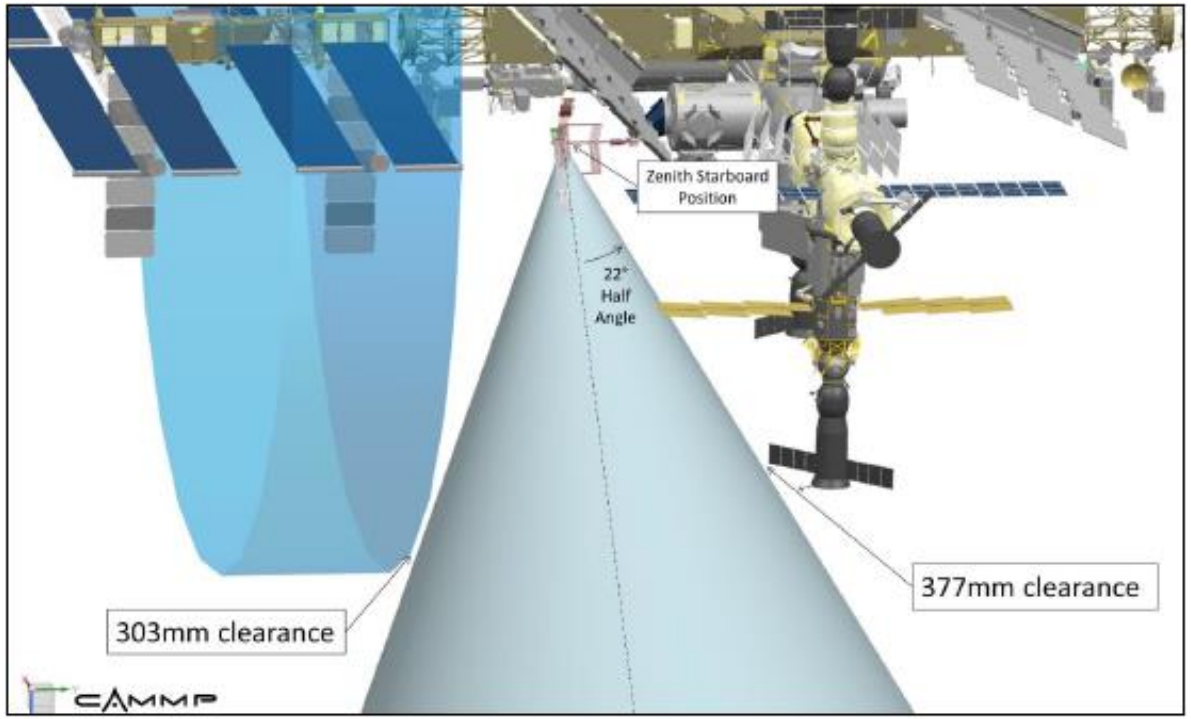
Components for the 2U qbee50-LTU-OC (SE01) CubeSat[11]

CubeSat System Options

- Single vs Constellation
- Communications
  - RF Signals
    - UHF
    - S-band
  - Ground Station only vs Intersatellite communication
  - Networks
    - KSAT
    - Globalstar

CubeSat Launch

- International Space Station (ISS)
  - NanoRacks (Industry Partner)
  - Lack of propulsion on CubeSat
  - ISS inclination and period
- Once launched, CubeSats adopt same orbit as ISS
  - Slight orbit deformation occurs due to CubeSats' ballistic coefficient



NanoRacks ISS Launcher[12]

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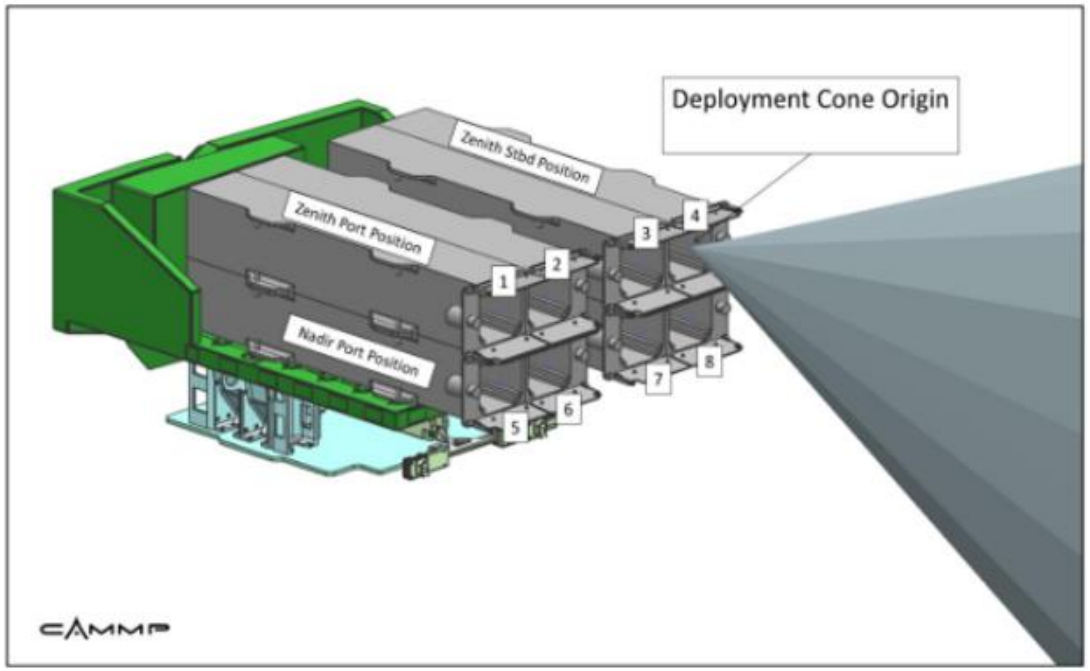
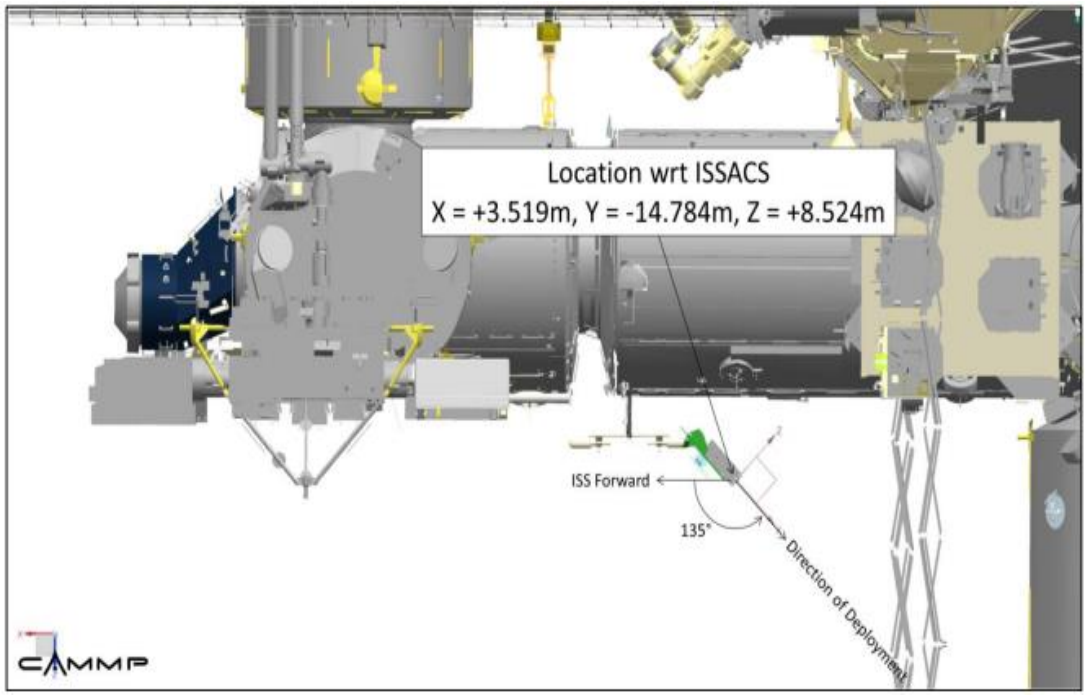
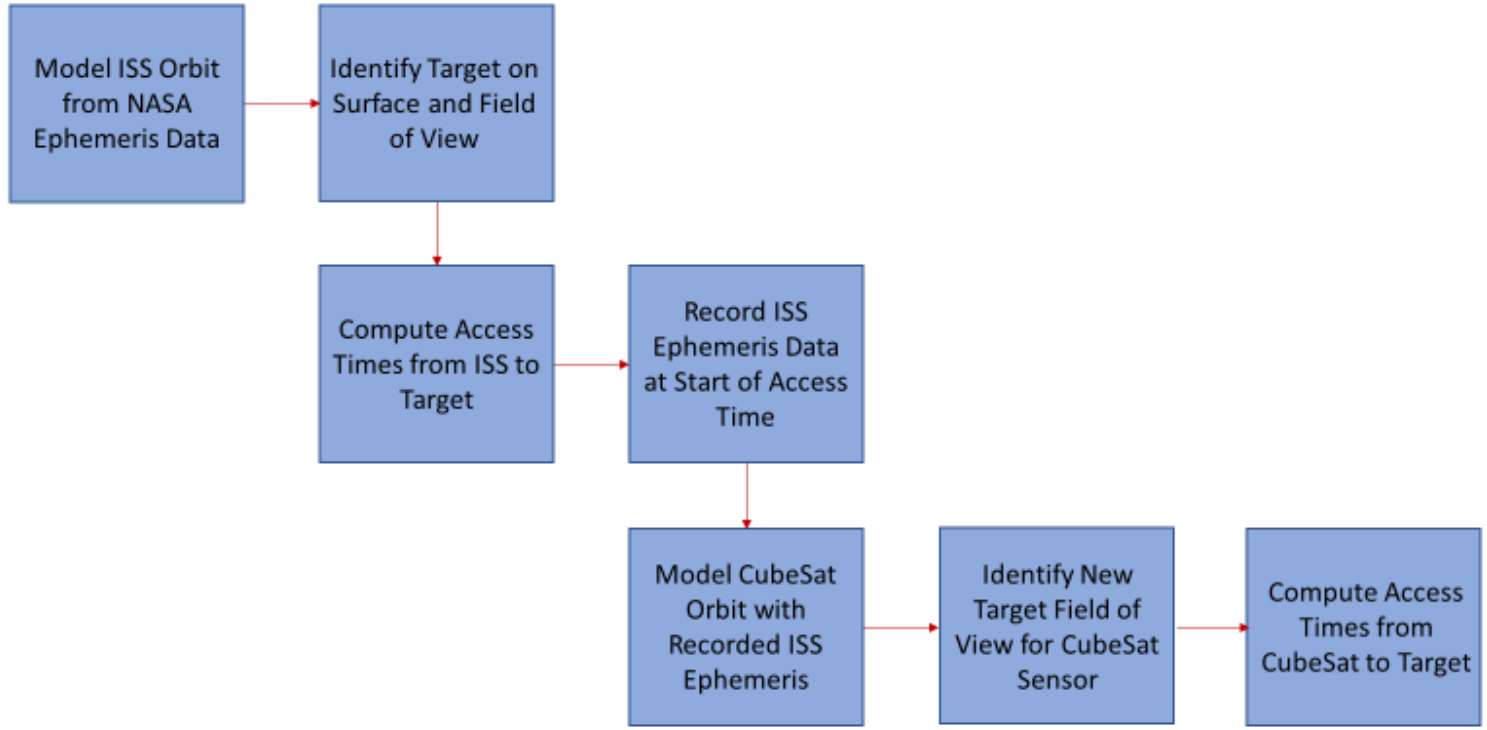


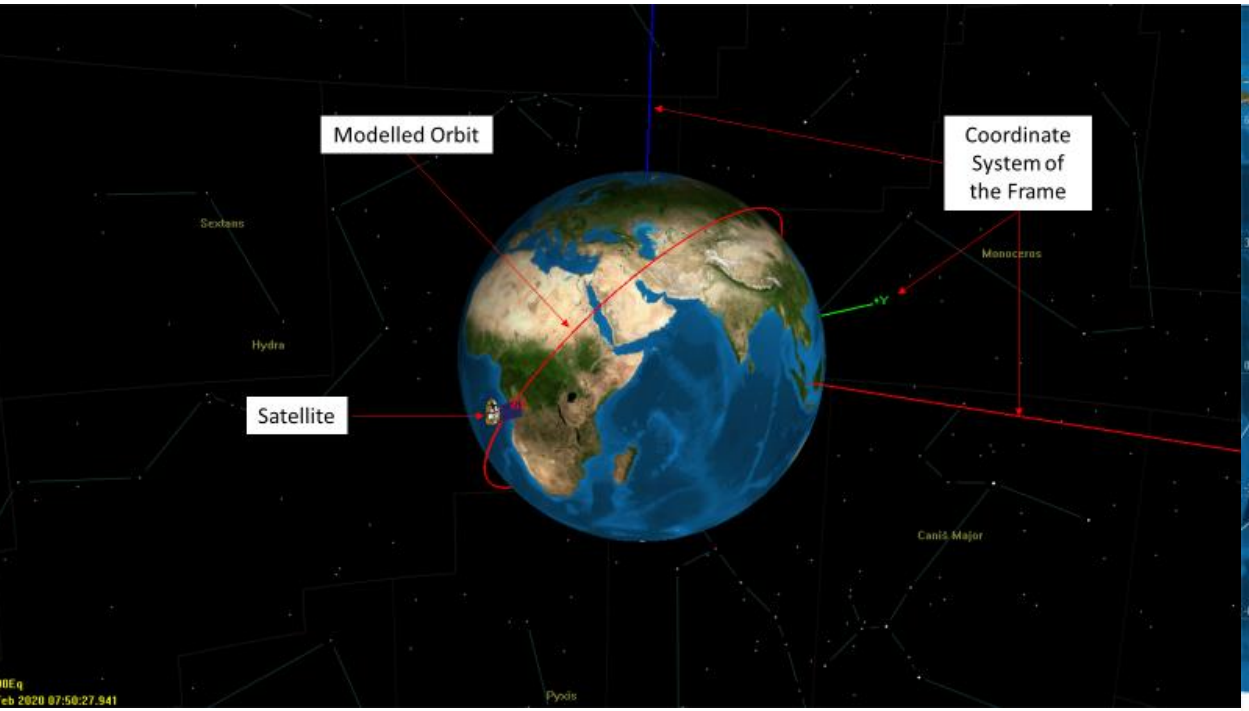


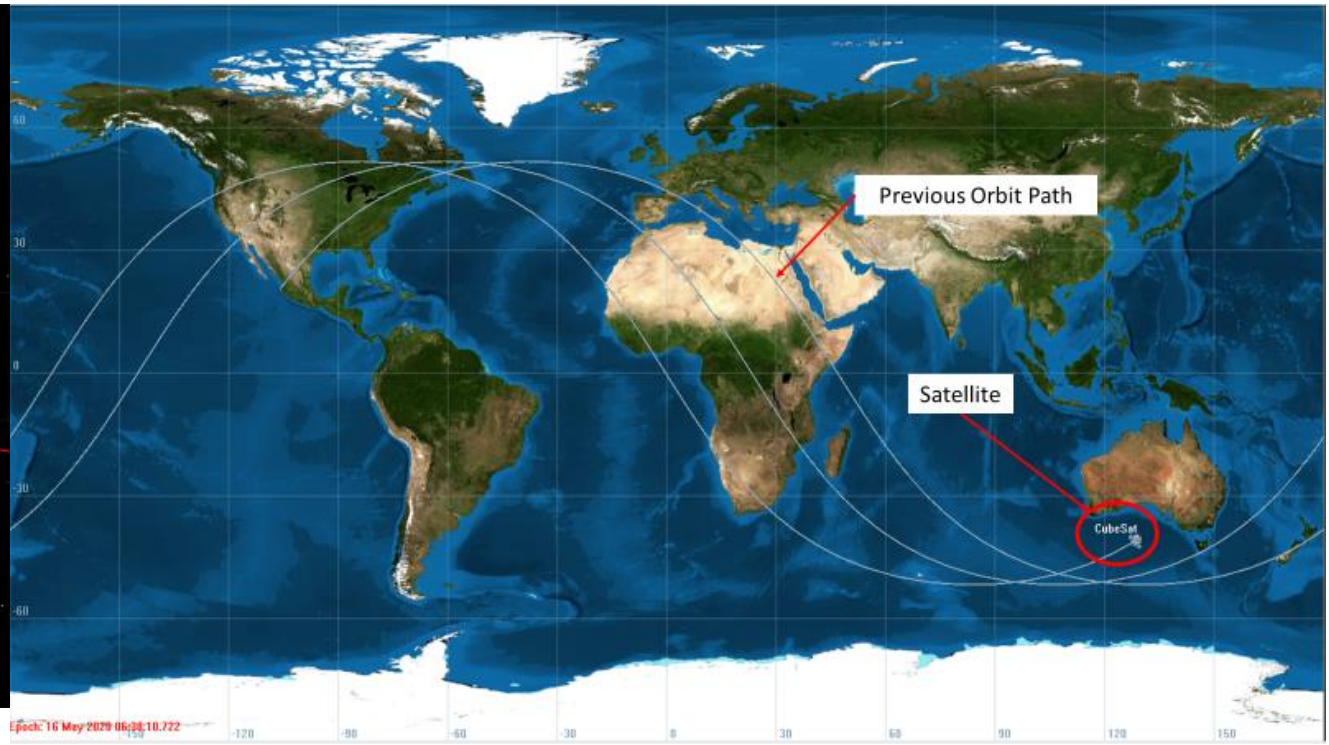
Orbital Modeling

Orbital Modelling Algorithm

- NASA General Mission Analysis Tool (GMAT)[13]
- NASA publishes ephemeris data for the ISS daily



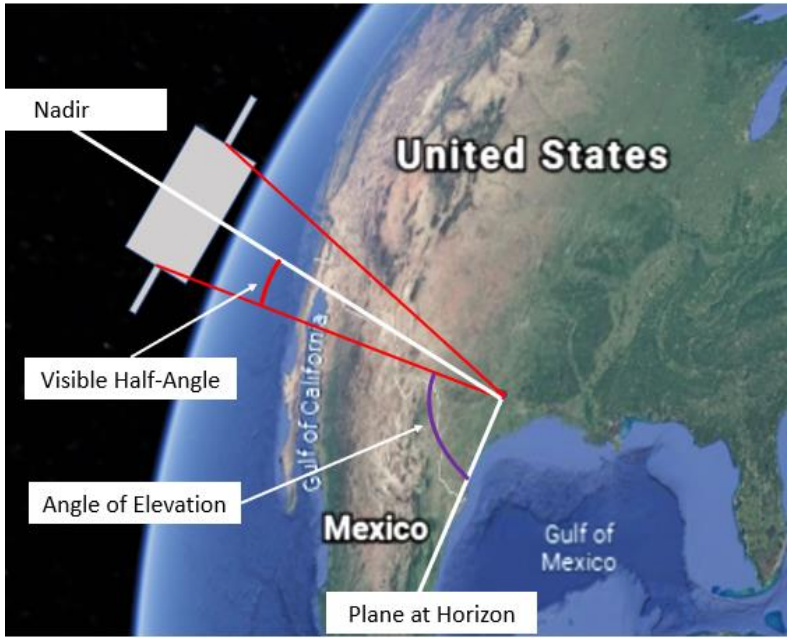

Modelled Orbit
Coordinate System of the Frame
Satellite
Sextans
Hydra
Monoceros
Canis Major
Pyxis


Previous Orbit Path
Satellite
CubeSat

The start time, stop time, and total duration in seconds of the ISS access times to College Station between May 16th and May 17th, 2020.

Start Time (UTC)	Stop Time (UTC)	Duration (s)
16 May 2020 02:21:11.119	16 May 2020 02:28:50.439	459.320
16 May 2020 04:00:24.049	16 May 2020 04:03:58.692	214.643
16 May 2020 08:55:58.427	16 May 2020 08:59:33.090	241.663
16 May 2020 10:31:06.514	16 May 2020 10:38:46.245	459.730
17 May 2020 01:33:35.889	17 May 2020 01:40:56.842	440.953
17 May 2020 03:11:22.331	17 May 2020 03:16:58.536	336.205
17 May 2020 09:43:24.391	17 May 2020 09:50:51.132	446.742
17 May 2020 11:21:24.435	17 May 2020 11:25:42.474	258.039

Angle of Elevation

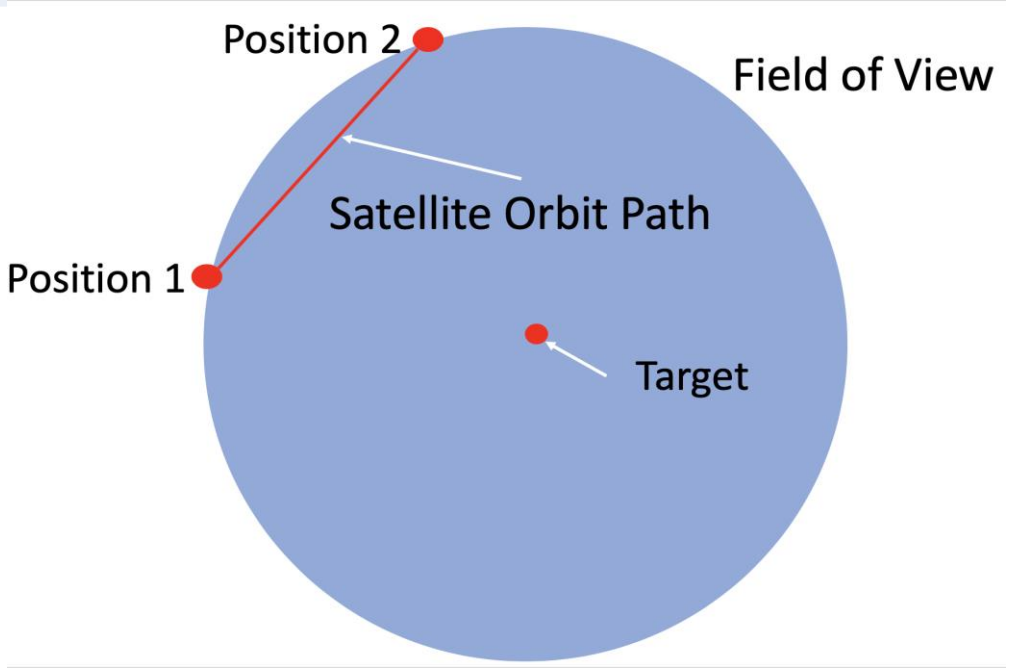


The start time, stop time, and total duration in seconds of a CubeSat access times to College Station between May 16th and May 17th, 2020.

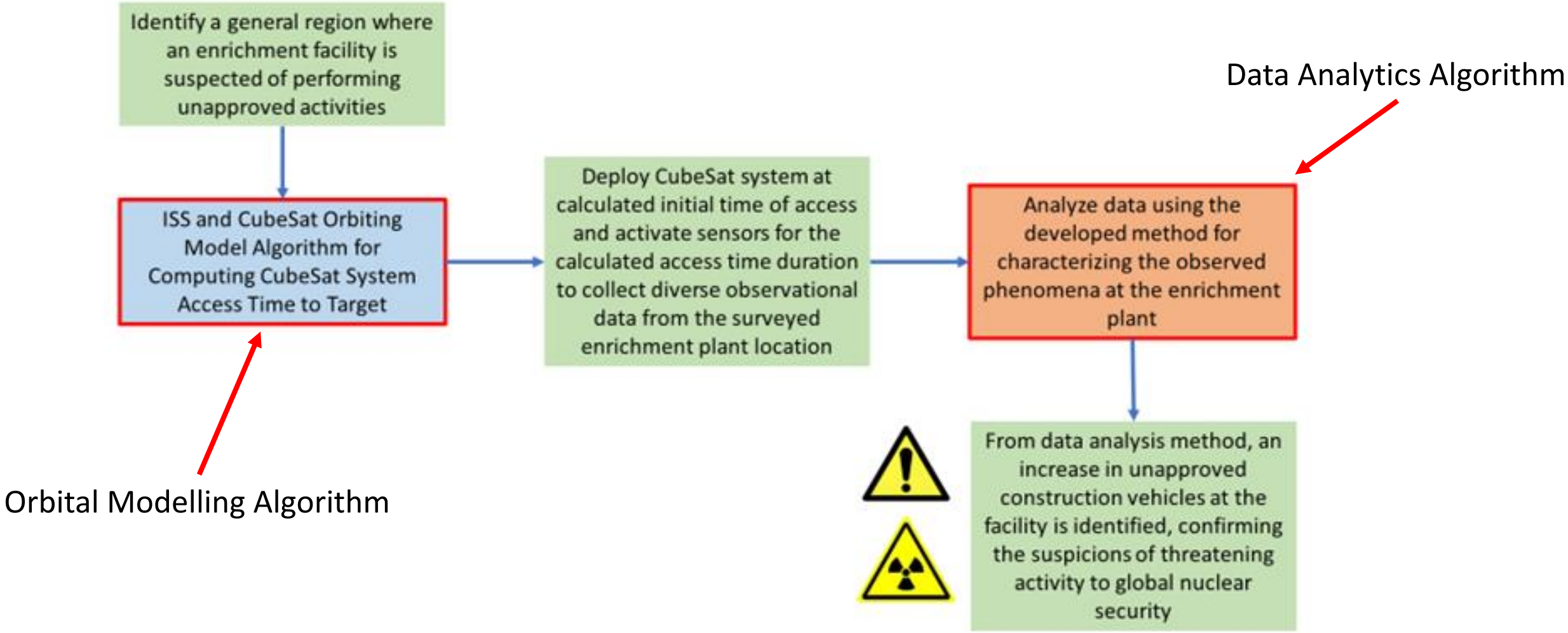
Start Time (UTC)	Stop Time (UTC)	Duration (s)
16 May 2020 02:24:28.108	16 May 2020 02:25:31.255	63.147
16 May 2020 10:33:28.336	16 May 2020 10:34:31.426	63.090

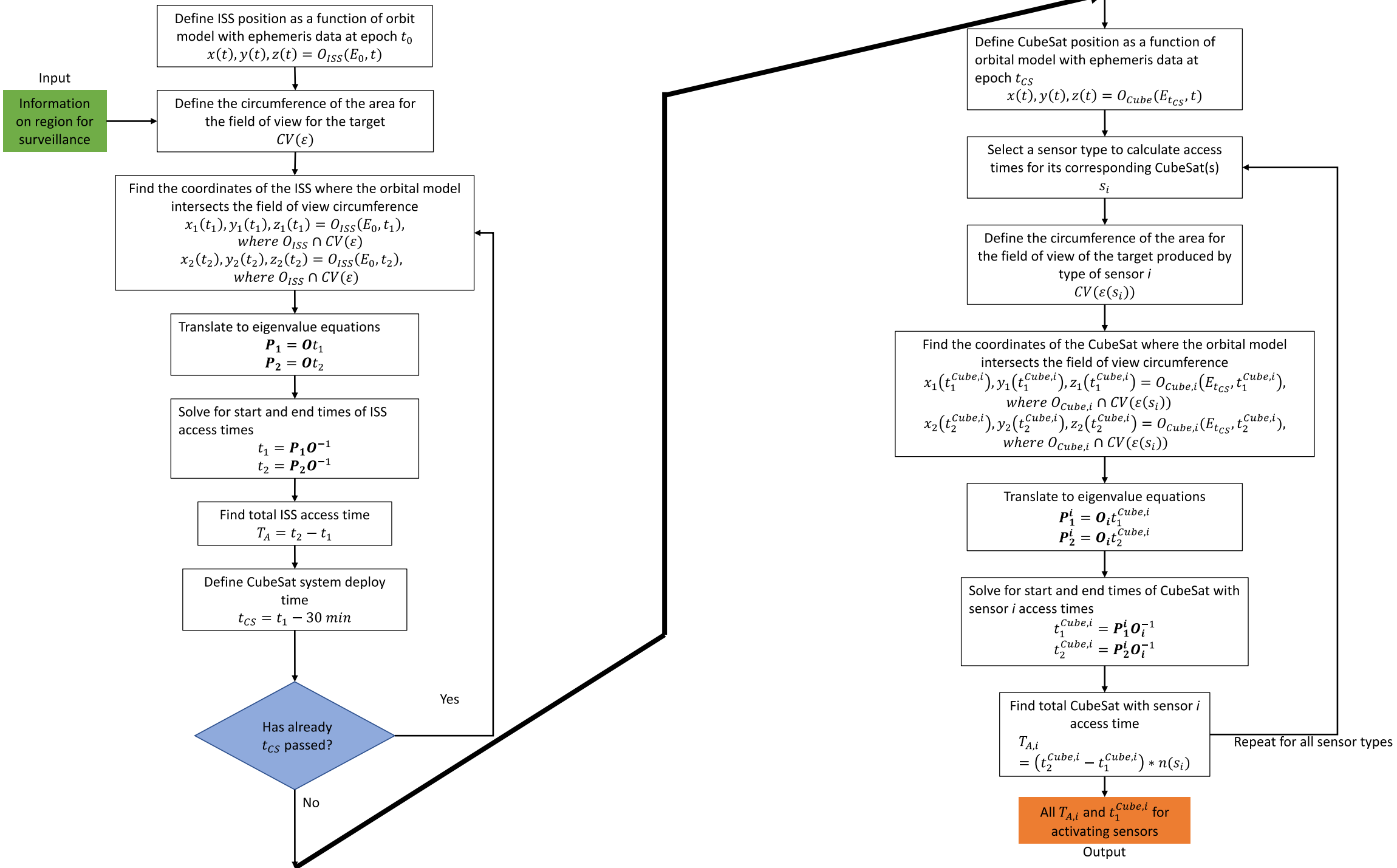
Influences sensing time

Sensor Angle of Elevation



Interface Between Algorithms and Data




Define ISS position as a function of orbit model with ephemeris data at epoch t_0
$x(t), y(t), z(t) = O_{ISS}(E_0, t)$
Input
Information on region for surveillance
Define the circumference of the area for the field of view for the target
$CV(\varepsilon)$
Find the coordinates of the ISS where the orbital model intersects the field of view circumference
$x_1(t_1), y_1(t_1), z_1(t_1) = O_{ISS}(E_0, t_1)$, $where\ O_{ISS} \cap CV(\varepsilon)$
$x_2(t_2), y_2(t_2), z_2(t_2) = O_{ISS}(E_0, t_2)$, $where\ O_{ISS} \cap CV(\varepsilon)$
Translate to eigenvalue equations
$\boldsymbol{P_1} = \boldsymbol{O}t_1$
$\boldsymbol{P_2} = \boldsymbol{O}t_2$
Solve for start and end times of ISS access times
$t_1 = \boldsymbol{P_1}\boldsymbol{O}^{-1}$
$t_2 = \boldsymbol{P_2}\boldsymbol{O}^{-1}$
Find total ISS access time
$T_A = t_2 - t_1$
Define CubeSat system deploy time
$t_{CS} = t_1 - 30\ min$
Has already t_{CS} passed?
Yes
No
Define CubeSat position as a function of orbital model with ephemeris data at epoch t_{CS}
$x(t), y(t), z(t) = O_{Cube}(E_{t_{CS}}, t)$
Select a sensor type to calculate access times for its corresponding CubeSat(s)
s_i
Define the circumference of the area for the field of view of the target produced by type of sensor i
$CV(\varepsilon(s_i))$
Find the coordinates of the CubeSat where the orbital model intersects the field of view circumference
$x_1(t_1^{Cube,i}), y_1(t_1^{Cube,i}), z_1(t_1^{Cube,i}) = O_{Cube,i}(E_{t_{CS}}, t_1^{Cube,i})$, $where\ O_{Cube,i} \cap CV(\varepsilon(s_i))$
$x_2(t_2^{Cube,i}), y_2(t_2^{Cube,i}), z_2(t_2^{Cube,i}) = O_{Cube,i}(E_{t_{CS}}, t_2^{Cube,i})$, $where\ O_{Cube,i} \cap CV(\varepsilon(s_i))$
Translate to eigenvalue equations
$\boldsymbol{P_1^i} = \boldsymbol{O_i}t_1^{Cube,i}$
$\boldsymbol{P_2^i} = \boldsymbol{O_i}t_2^{Cube,i}$
Solve for start and end times of CubeSat with sensor i access times
$t_1^{Cube,i} = \boldsymbol{P_1^i}\boldsymbol{O_i}^{-1}$
$t_2^{Cube,i} = \boldsymbol{P_2^i}\boldsymbol{O_i}^{-1}$
Find total CubeSat with sensor i access time
$T_{A,i} = (t_2^{Cube,i} - t_1^{Cube,i}) * n(s_i)$
Repeat for all sensor types
All $T_{A,i}$ and $t_1^{Cube,i}$ for activating sensors
Output

Conclusions and Future Work

Conclusions

- Phenomena of interest identified
- CubeSat architecture identified
- Orbital capabilities identified
- Development of algorithm for orbital data
- **CubeSats are viable surveillance platforms for nuclear security**

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Future Work

- Develop surrogate dataset of representative data
- Develop anomaly detection methodology for characterization on surrogate dataset
- Create illustrative applications of the technology

Task 2: Specification development for a CubeSat-based global surveyor

2.1. CubeSat very high-resolution sensing options with focus on optical image analysis, reconstruction and signature development

2.2. Multi-modal spectral signature analysis options in CubeSat architectures

2.3. Hardware specification development and integration options analysis

Task 3: Computational and experimental program based on surrogate and simulated data sets demonstrating capabilities of the proposed orbital surveyor platform

3.1. 3D surface and atmospheric mapping method with dynamic feature localization and analysis

3.2. CubeSat surveyor performance model and data simulation

3.3. Data analytics demonstration program based on high-resolution multi-modal signatures (land and atmospheric mapping, feature extraction, object recognition) – human activity localization, activity detection and interpretation with resolutions higher than 5m.

Task 4: CubeSat design and data analysis towards a future demonstration launch program

4.1. Data analysis and data acquisition system development and specification in support of the CubeSat surveyor architectures

4.2. Data analytics methods including fusion (spatial, spectral, scale-space adaptations) and machine learning based on Cube Sat data streams

4.3. Design of a CubeSat-based global surveyor and the launch program development

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Questions?

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