CONOPS & Experiment Plan

23 February 2022

Kate Yoshino, AFRL/RV

Hi, I’m Kate.

UNP alumna, NS-8

UNP PMO, Systems Engineer

SMALL SATELLITE PORTFOLIO
AIR FORCE RESEARCH LABORATORY

Mission Manager

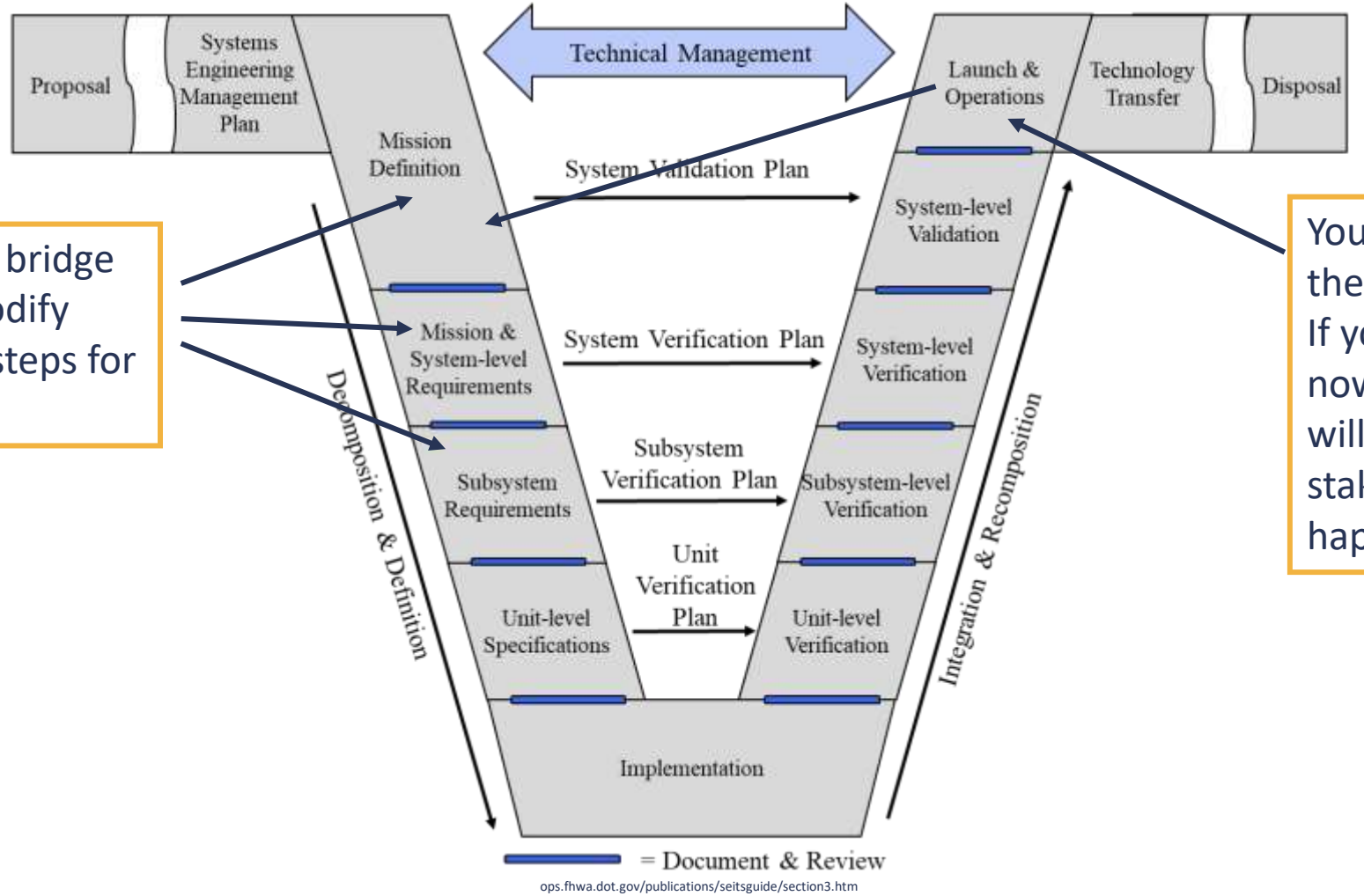
Today, we're talking about…

- CONOPS & Experiment Plan
- Learning Objectives
  - How do these fit together?
  - How do they fit into the development process?
  - Why do they matter?
  - What are the key elements?

Definitions & Context

Why does this matter?

CONOPS helps bridge this gap and codify each of these steps for a satellite!



ops.fhwa.dot.gov/publications/seitsguide/section3.htm

You have to plan for the end!
If you establish a plan now, your operators will thank you and the stakeholders will be happy.

Definitions

Mission Objectives/Design Document

- Describes the need, goals, and the “why”
- Mission Objectives
- Success Criteria
- Customer/end user definition
- Scope of mission

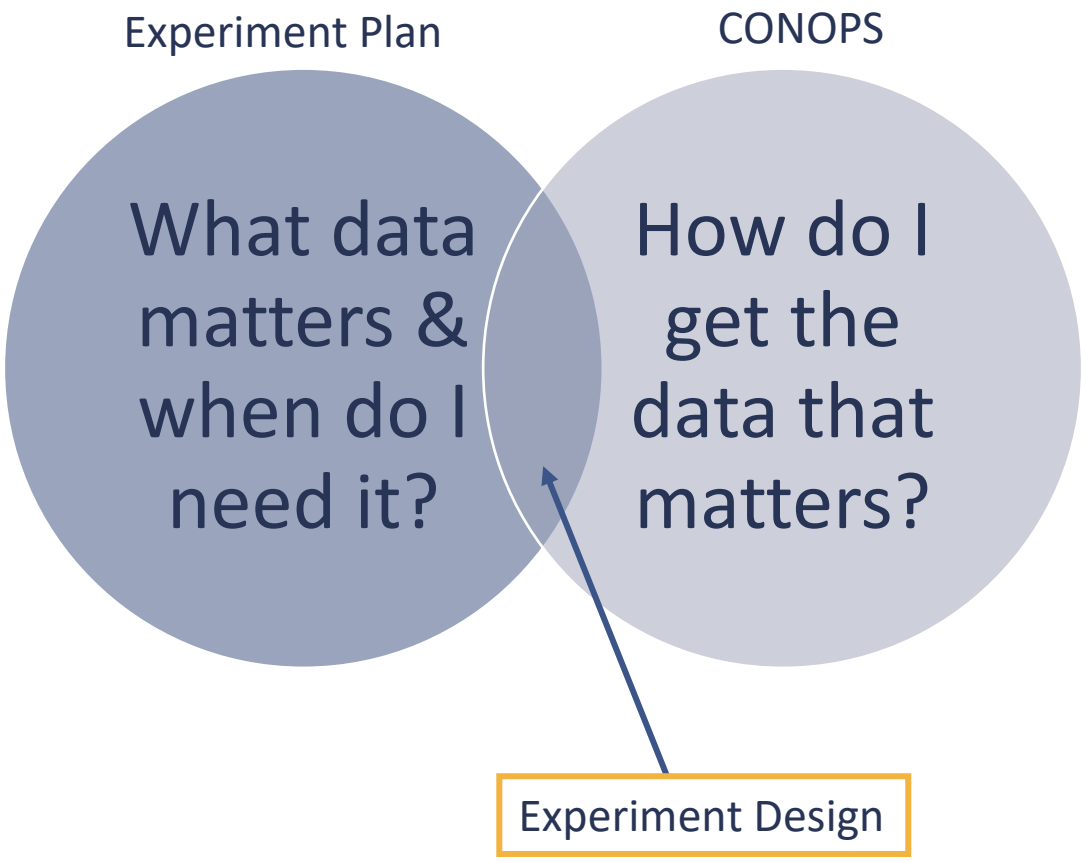
Experiment Plan

- Describes goal targets, test parameters/framework, and the “what”
- Experiment goals/framework
- Key parameters
- Defining meaningful data
- Defining meaningful cadence/timeline

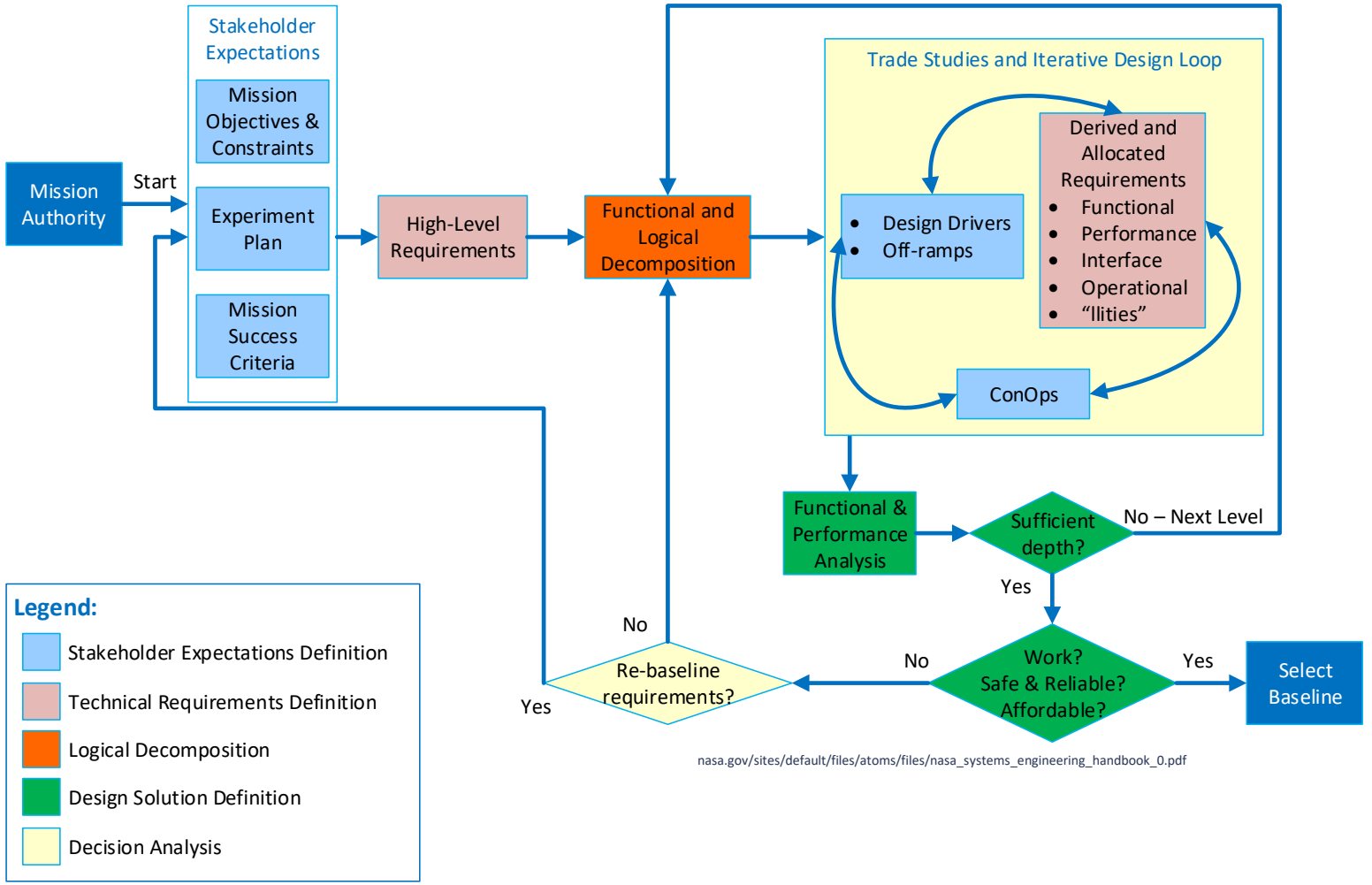
Concept of Operations

- Describes the flow of action, situational considerations, and the “how”
- Describes how experiment can be achieved on a pass-to-pass / designed basis
- Considers off-nominal cases
- Considers software behavior
- Considers spacecraft operations around/that facilitate experiment

CONOPS vs Experiment Plan



CONOPS, Experiment Plan, & System Design



nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

Example Mission Set

Mission Statement

- Count vehicles in specific areas from a space-based platform to determine consumer traffic trends in order to assess parking needs [and traffic flow].

Mission Objectives

- MO-1: Identify vehicles within an image with 90% accuracy
- MO-2: Image same location at least once daily
- MO-3: Geolocate image to within 50 meters

Mission Success Criteria

- MSC: Obtain car quantity for 1 location at the same time daily for 7 days
- FSC: Obtain car quantity for 5 locations at the same time daily for 49 days

Experiment Plan

Experiment Plan

What are we doing, and what do we need to do to make it meaningful?

Mission Statement

- Count vehicles in specific areas from a space-based platform to determine consumer traffic trends in order to assess parking needs [and traffic flow].

Mission Objectives

- MO-1: Identify vehicles within an image with 90% accuracy
- MO-2: Image same location at least once daily
- MO-3: Geolocate image to within 50 meters

Mission Success Criteria

- MSC: Obtain car quantity for 1 location at the same time daily for 7 days
- FSC: Obtain car quantity for 5 locations at the same time daily for 49 days

Key Questions:

- What locations matter?
- What are location priorities?
- How will we post-process data products?
- What time cadence is meaningful?
- What resolution is meaningful?
- Can I capture multiple locations in a single pass?
- What time of day is meaningful?
- What are the Key Performance Indicators/Parameters?
- How many passes does the experiment take?

We know what our mission should do, but we might not know enough to design yet…

Experiment Plan Elements

Experiment Definition

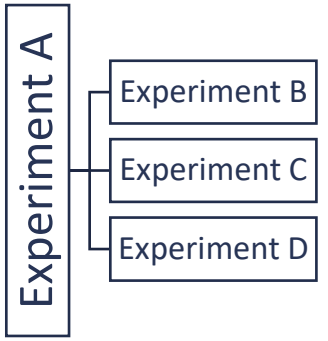
Experiment Priority

Experiment Parameters

Or

Experiment A
(and that's it!)

Or



Objectives	What is this specific experiment trying to achieve?
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?
Experiment Success/completion criteria	What information do you need to achieve experiment completion?
Data Telemetry & Products	What data do you need to answer the last question? (just payload data? Additional telemetry?)
Timing "requirements"	Do experiments need to happen at a specific time? What about relative time? Does it need to last a specific time?
Ground configuration	Are there relative spacing considerations required?
Spacecraft configuration	What does my satellite need to facilitate? What non-payload subsystems are required?

Example Experiment Plan Excerpt
Experiment Definition

Mission Statement

- Count vehicles in specific areas from a space-based platform to determine consumer traffic trends in order to assess parking needs [and traffic flow].

Mission Objectives

- MO-1: Identify vehicles within an image with 90% accuracy
- MO-2: Image same location at least once daily
- MO-3: Geolocate image to within 50 meters

Mission Success Criteria

- MSC: Obtain car quantity for 1 location at the same time daily for 7 days
- FSC: Obtain car quantity for 5 locations at the same time daily for 49 days

Perhaps one of the most beneficial things about an experiment plan is garnering clarification from stakeholders

This leads to questions regarding data integrity and data processing. That is key in experiment design!

There must be a prioritized location. And we can guess that 7 days is significant as a week. This could be a single experiment!

Now, we're expanding to 5 locations. And for a longer duration. Are these 5 areas co-located?

So you meet success at 50 days… then what?

Example Experiment Plan Excerpt
Experiment Definition

Mission Statement

- Count vehicles in specific areas from a space-based platform to determine consumer traffic trends in order to assess parking needs [and traffic flow].

Mission Objectives

- MO-1: Identify vehicles within an image with 90% accuracy
- MO-2: Image same location at least once daily
- MO-3: Geolocate image to within 50 meters

Mission Success Criteria

- MSC: Obtain car quantity for 1 location at the same time daily for 7 days
- FSC: Obtain car quantity for 5 locations at the same time daily for 49 days

This leads to questions regarding data integrity and data processing. That is key in experiment design!

There must be a prioritized location. And we can guess that 7 days is significant as a week. This could be a single experiment!

Now, we're expanding to 5 locations. And for a longer duration. Are these 5 areas co-located?

So you meet success at 50 days… then what?

Experiment A – Single site

- Dedicate one week to minimum mission success

Experiment B – Single, but new site

- Repeat experiment A for the second highest priority

Experiment C – Co-located sites

- Using the same aperture, collect on five sites and post process for 49 days

Experiment D – multiple non-collocated sites

- A city in a nearby state can leverage this same satellite asset, but additional collection is desired

Experiment E – Same sites as B but at different season

- Repeat experiment B but in a different month to assess seasonal affects

Example Experiment Plan Excerpt
Experiment Priority

Experiment A – Single site
- Dedicate one week to minimum mission success

Experiment B – Single, but new site
- Repeat experiment A for the second highest priority

Experiment C – Co-located sites
- Using the same aperture, collect on five sites and post process for 49 days

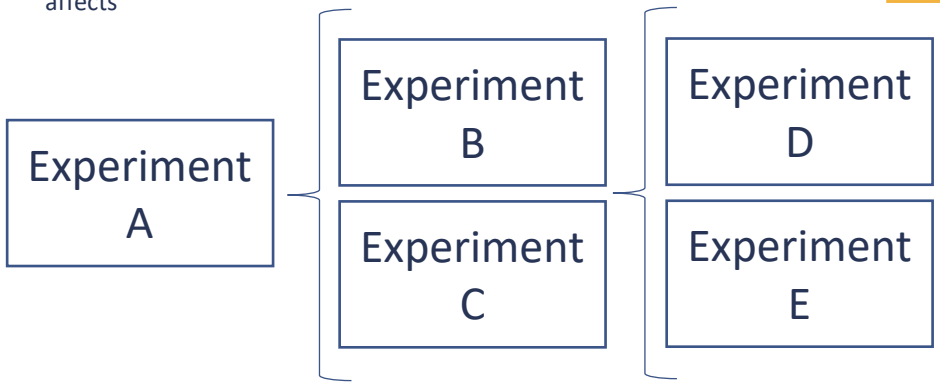
Experiment D – multiple non-collocated sites
- A city in a nearby state can leverage this same satellite asset, but additional collection is desired

Experiment E – Same sites as B but at different season
- Repeat experiment B but in a different month to assess seasonal affects

Minimum Success

Full Success

"Design line"
Always design to full success. Beyond that plan and accommodate as resources allow!



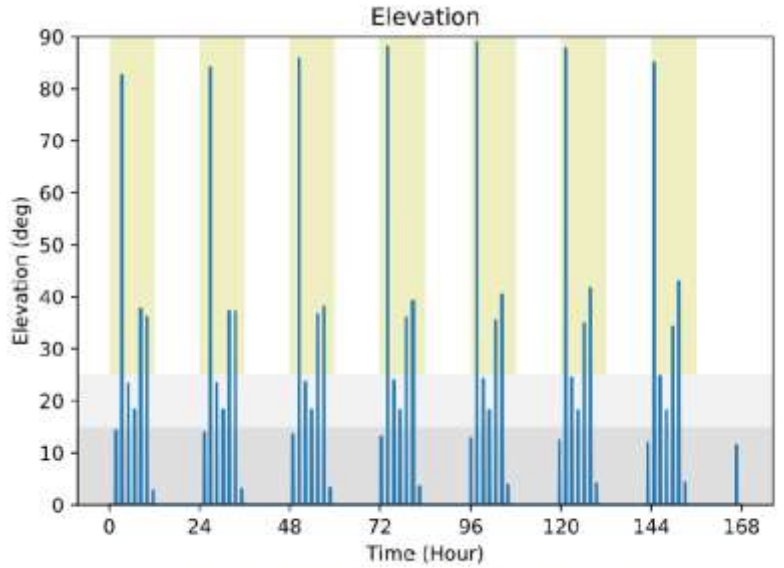


Figure 5. Passes For 500 km Altitude 45 Degree Inclination

Considerations:
- I can get 4-5 decent passes in a day
  - If I have one good pass each day, I should use that on Experiment A
- Can I power my payload in consecutive passes?
- What maneuvering is required?
- How do I know where I am pointing?

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks

Trading resolution vs field of view vs meaningful proximity of locations

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability

Consider CONOPS, system budgets, thermal conditions, experiment prerequisites, etc.

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability
Experiment Success/completion criteria	What information do you need to achieve experiment completion?	Time-stamped image	Time-stamped image

Data product. Think "what will go into the report"

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability
Experiment Success/completion criteria	What information do you need to achieve experiment completion?	Time-stamped image	Time-stamped image
Data Telemetry & Products	What data do you need to answer the last question? (just payload data? Additional telemetry?)	Spacecraft time, image, position, pointing telemetry	Spacecraft time, image, position, pointing telemetry

You can't just have pictures- other context is also needed!

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability
Experiment Success/completion criteria	What information do you need to achieve experiment completion?	Time-stamped image	Time-stamped image
Data Telemetry & Products	What data do you need to answer the last question? (just payload data? Additional telemetry?)	Spacecraft time, image, position, pointing telemetry	Spacecraft time, image, position, pointing telemetry
Timing "requirements"	Do experiments need to happen at a specific time? What about relative time? Does it need to last a specific time?	Daily! (see plot on last slide) ASAP	Daily! (see plot on last slide) ASAP

An opportunity to also assess data value from customer- "what if I skip a day?"

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability
Experiment Success/completion criteria	What information do you need to achieve experiment completion?	Time-stamped image	Time-stamped image
Data Telemetry & Products	What data do you need to answer the last question? (just payload data? Additional telemetry?)	Spacecraft time, image, position, pointing telemetry	Spacecraft time, image, position, pointing telemetry
Timing "requirements"	Do experiments need to happen at a specific time? What about relative time? Does it need to last a specific time?	Daily! (see plot on last slide) ASAP	Daily! (see plot on last slide) ASAP
Ground configuration	Are there relative spacing considerations required?	See plot last slide	Extend timeline on last slide Consider post-processing tools!
Spacecraft configuration	What does my satellite need to facilitate? What non-payload subsystems are required?	Ground tracking ADCS mode	Ground tracking ADCS mode

Time window of access of passes may move. Is that ok? By how much?

How will you do data processing? With what timeliness is that required?

Example Experiment Plan Excerpt
Experiment Parameters

		Experiment A	Experiment C
Objectives	What is this specific experiment trying to achieve?	Post-process data for a single location image daily for one week	Post-process image identifying 5 locations in a single or a couple images daily for 7 weeks
Entry Criteria and/or Constraints	Are there CONOPS and/or external drivers impacting ability to run experiment?	Must have completed camera & ADCS check out. Must have fairly consistent access times/stable vehicle.	Must have completed experiment A. Must have vary consistent access times, data downlink windows, and vehicle stability
Experiment Success/completion criteria	What information do you need to achieve experiment completion?	Time-stamped image	Time-stamped image
Data Telemetry & Products	What data do you need to answer the last question? (just payload data? Additional telemetry?)	Spacecraft time, image, position, pointing telemetry	Spacecraft time, image, position, pointing telemetry
Timing "requirements"	Do experiments need to happen at a specific time? What about relative time? Does it need to last a specific time?	Daily! (see plot on last slide) ASAP	Daily! (see plot on last slide) ASAP
Ground configuration	Are there relative spacing considerations required?	See plot last slide	See plot last slide
Spacecraft configuration	What does my satellite need to facilitate? What non-payload subsystems are required?	Ground tracking ADCS mode	Ground tracking ADCS mode

Sometimes experiments are not all that different & that's ok!

Experiment Plan Informs…

- Orbital requirements
- Payload selection
- Mission scope
- Communication architecture considerations
- Design requirements (i.e. pointing requirements)
- System Budgets (power, link, pointing)
- Data processing requirements
- CONOPS!

CONOPS

CONOPS Elements

Mission Design	Mission Timeline*	Vehicle State Transitions and Fault Handling
• Tasking, Scheduling, and Control* • Budget considerations • Drives spacecraft & ground integrated system design/ communications architecture*	• Identification of success points • Prioritization of objectives and actions • Describe flow and decision points	• Definition of vehicle modes (informs budget and software) • Identifies some levels of fault handling • Identifies vehicle/operator touch points

*Taken from SMAD (Wertz & Larson, 2003)

Terminology

There is not a common vernacular associated with CubeSat CONOPS. The important thing is that you understand your own definitions within your team and when communicating externally.

For this presentation:

Experiment	Specifically defined, goal-oriented on-orbit test, collection, or demonstration directly tied to mission objectives
Mode	A software configuration that sets specific configuration for the vehicle
Phase	A period of time by which a collection of pre-defined activities is accomplished

CONOPS Elements

Mission Design

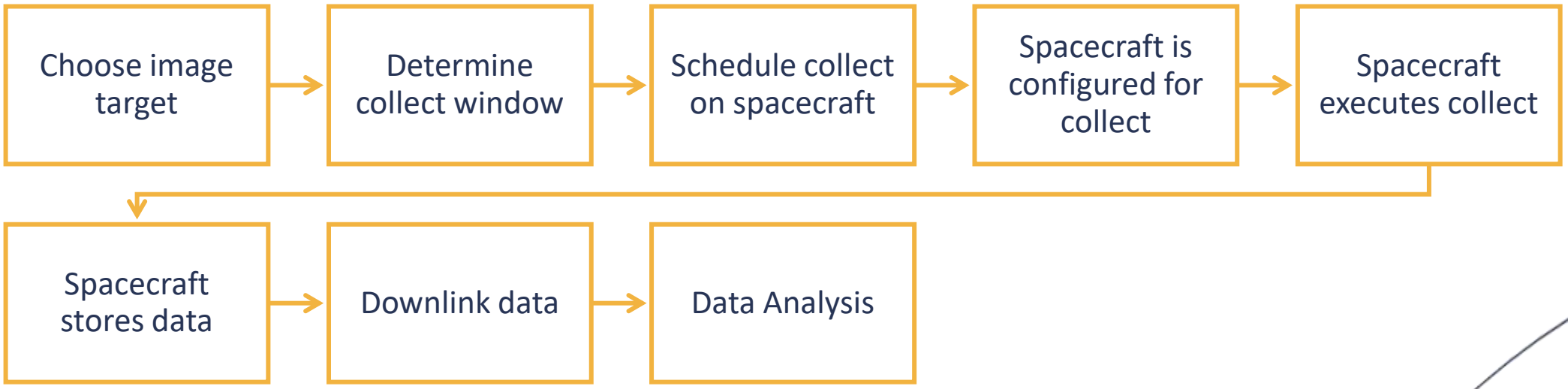
- Tasking, Scheduling, and Control*
- Budget considerations
- Drives spacecraft & ground integrated system design/ communications architecture*

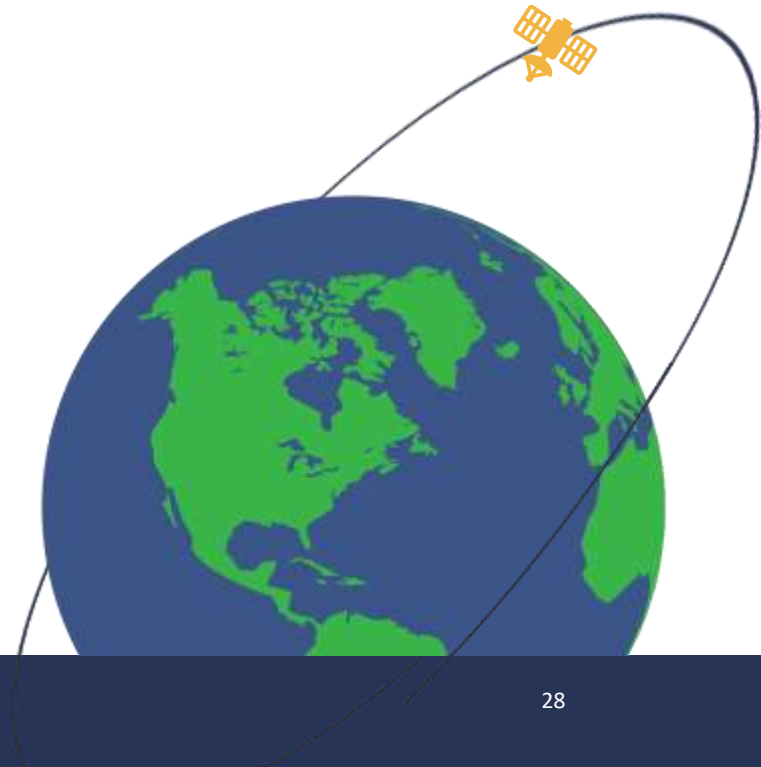
What is the experimental cadence?
What are the key vehicle functions in a given experiment?

How much power will an experiment require?
How much data will an experiment product?
How much downlink time do I need to acquire the data?
Is there a duration limit on a given experiment?

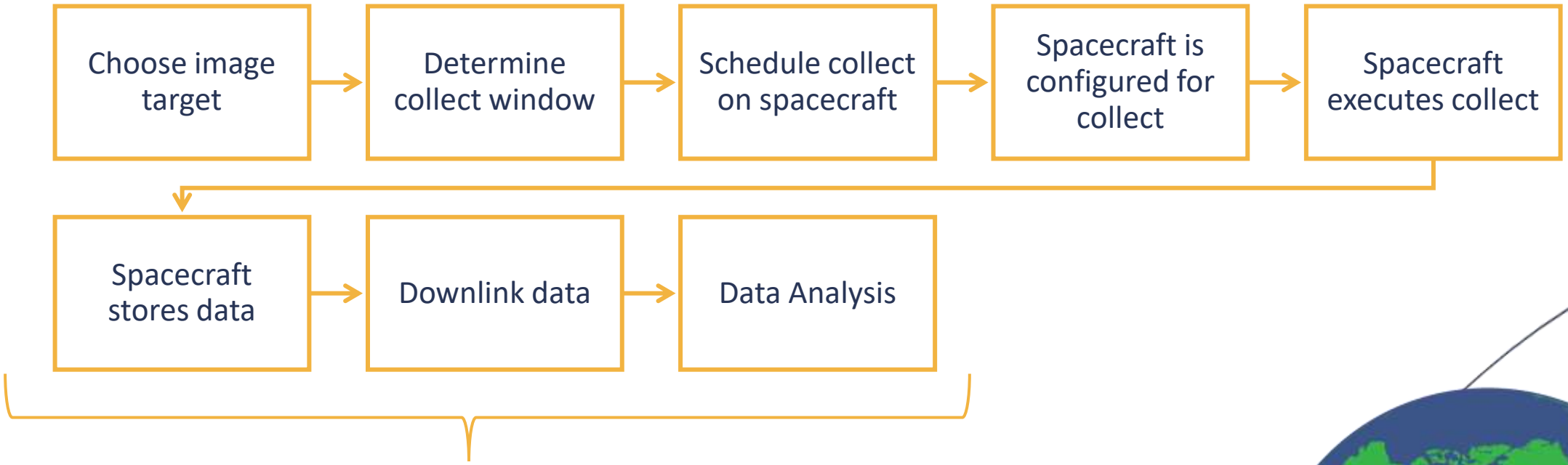
How many ground passes do I need each day?
How many ground stations do I need?
What are the core operator tools needed

CONOPS – Example Experiment A

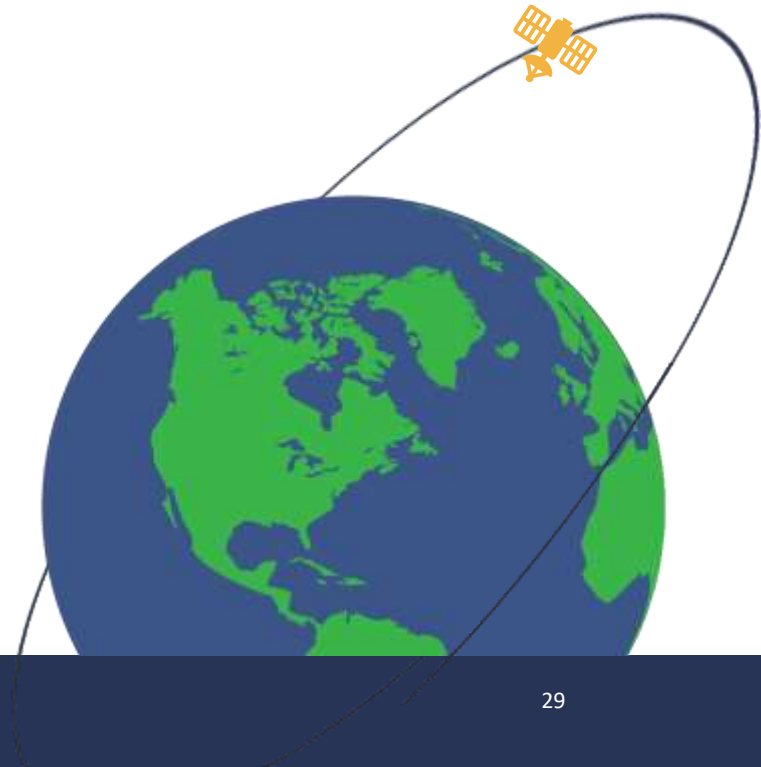




CONOPS – Example Experiment A



Seems simple at a high level, but **there is a lot of detail.**



For each image…

Considerations can be made that will feed into and from your system level budgets

- Data Collect –
  - How much payload data is generated?
  - How much vehicle telemetry is needed?
  - What is the total data generated?
  - How much power does a pass required? Do you need to be in sun?
  - Average pass time?
- Data downlink –
  - Avg. pass time 10 min
  - What is a good enough data rate?
  - How many passes can you take on downlink?
  - How quickly do you need data?

CONOPS & Spacecraft Design Considerations

Key Questions

- Can you downlink while collecting?
- Can you store the data on-board?
- How fast does the full loop (Data request – to –data receipt) need to be?
- Is data collect seasonal, time driven, time-of-day driven, etc.?
- How often do I need pictures?
- Do I need full pictures, or can I do processing on board?
- Will I survive power wise if I take pictures during eclipse?

CONOPS - Orbit

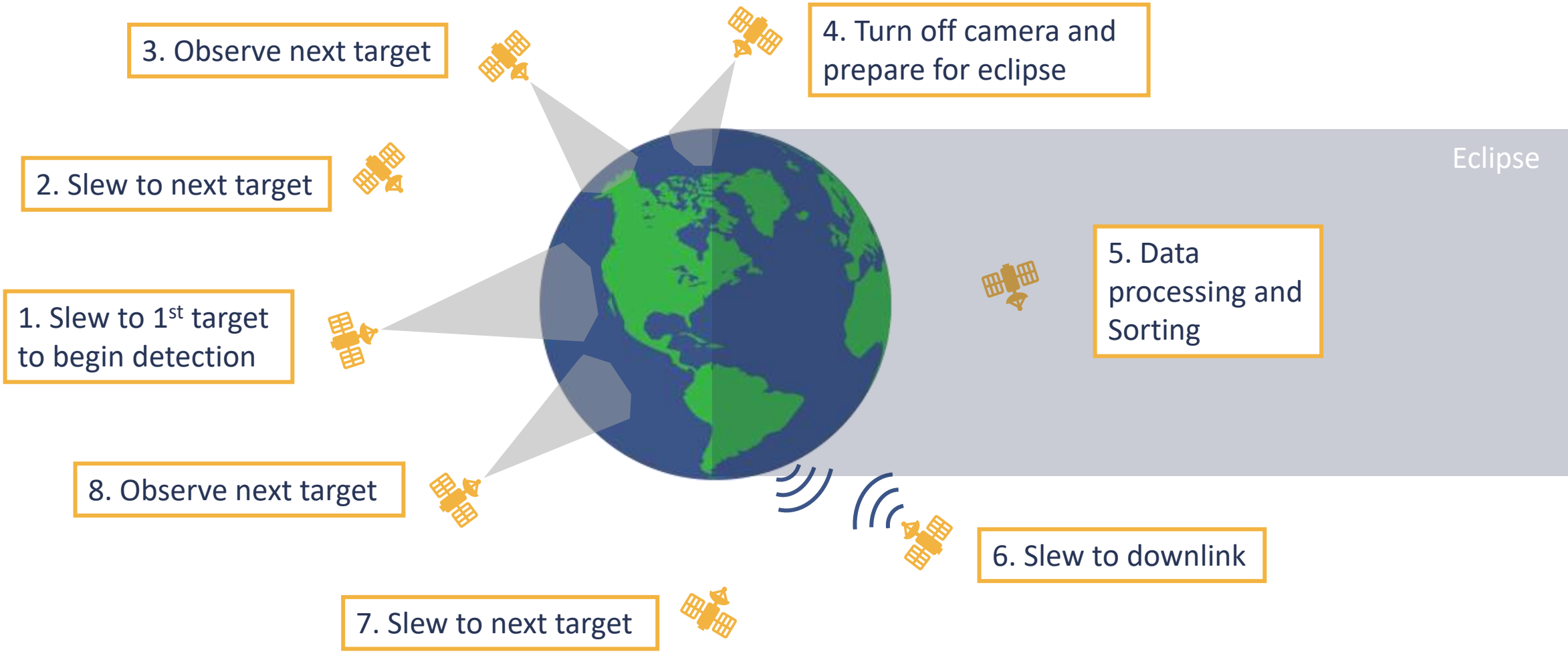
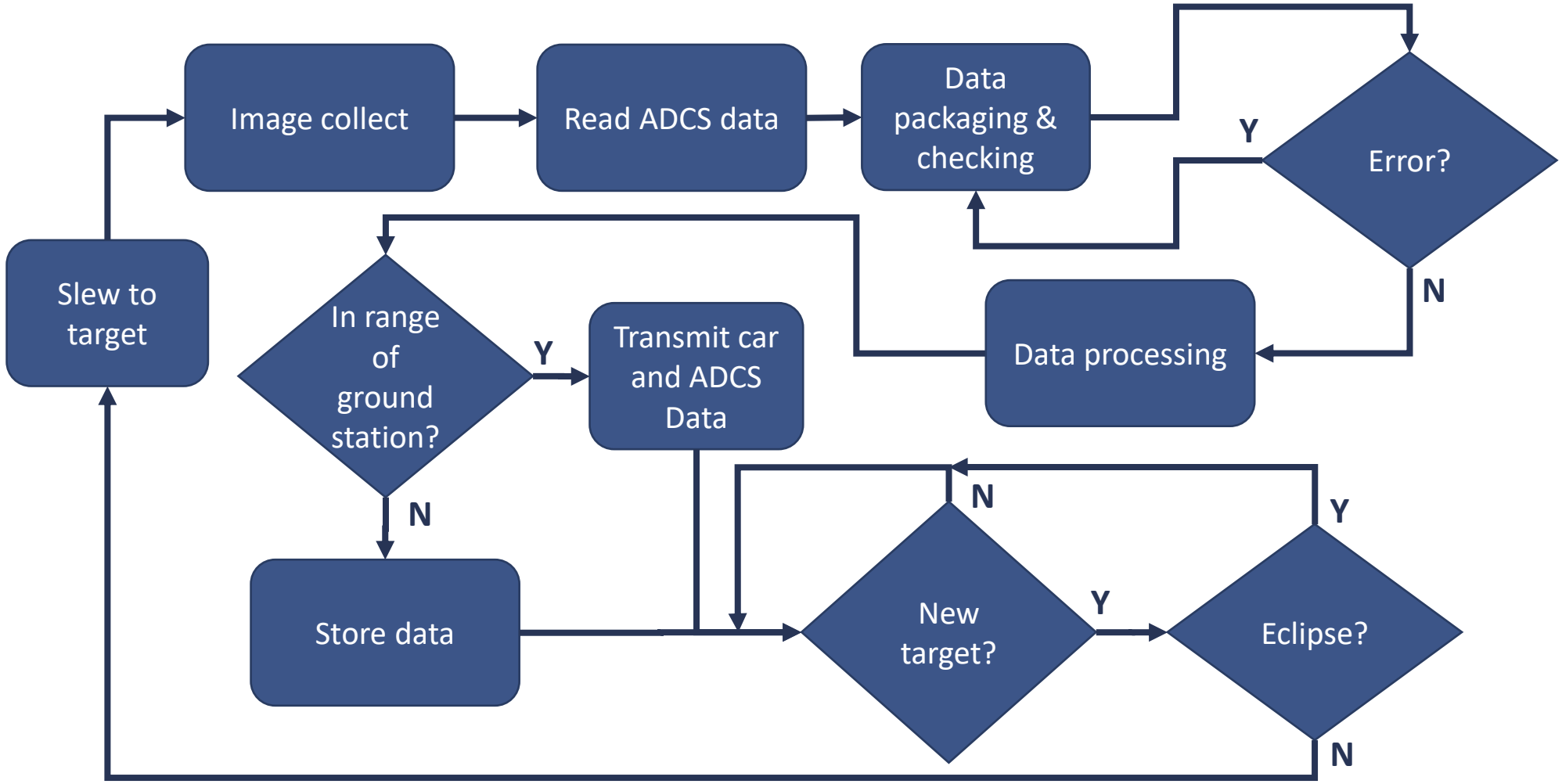
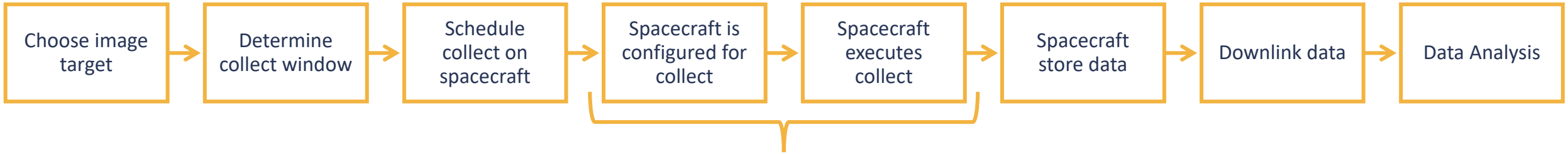


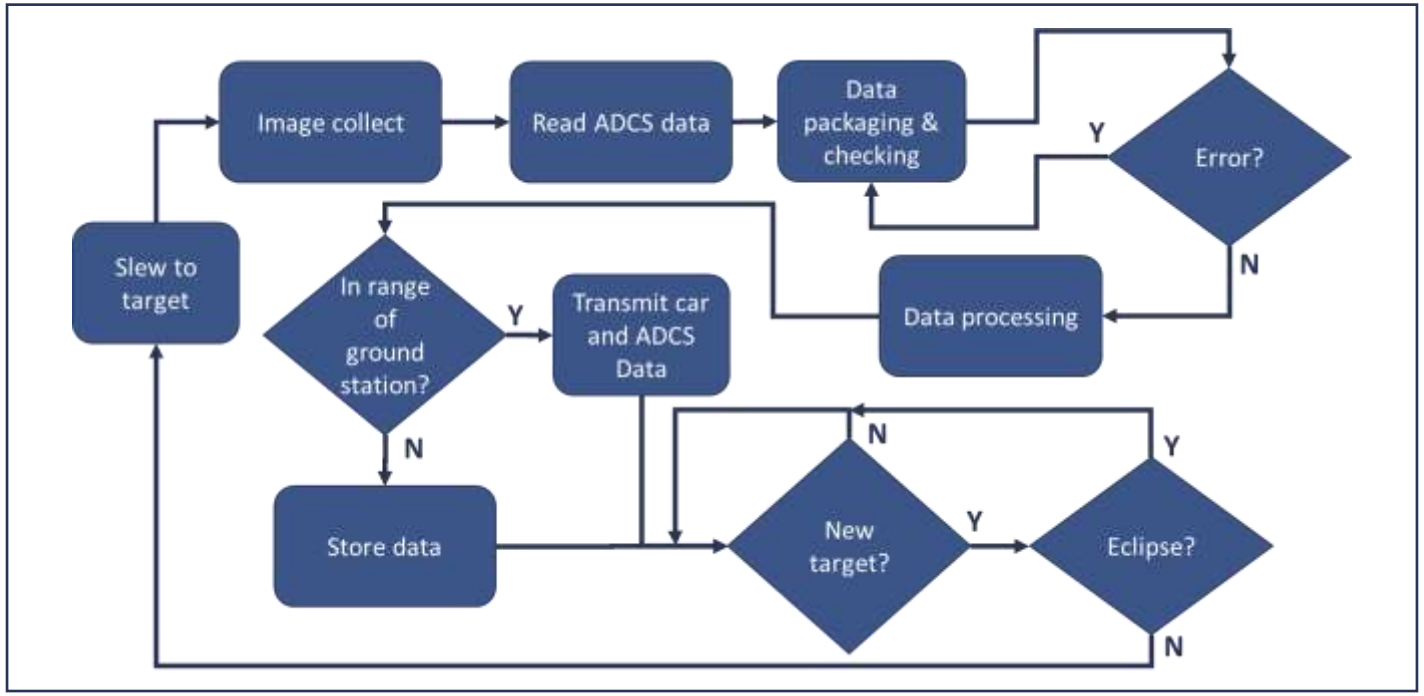
Image credits:
- Northropgrumman.com
- Videoblocks.com
- isispace.com
- Picsart.com

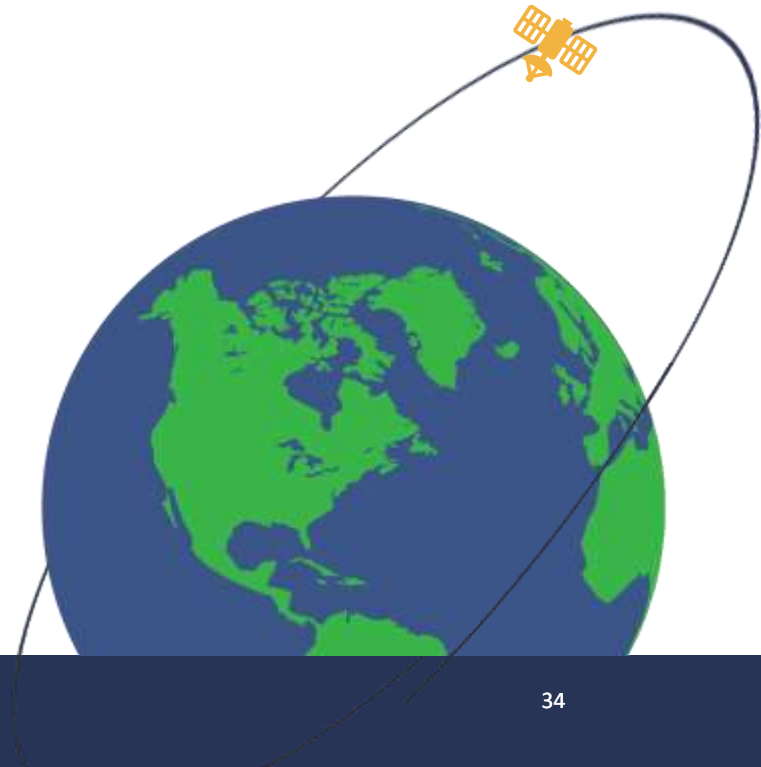
Revisiting a single data collect & transmit



CONOPS - Example Experiment A







CONOPS Elements

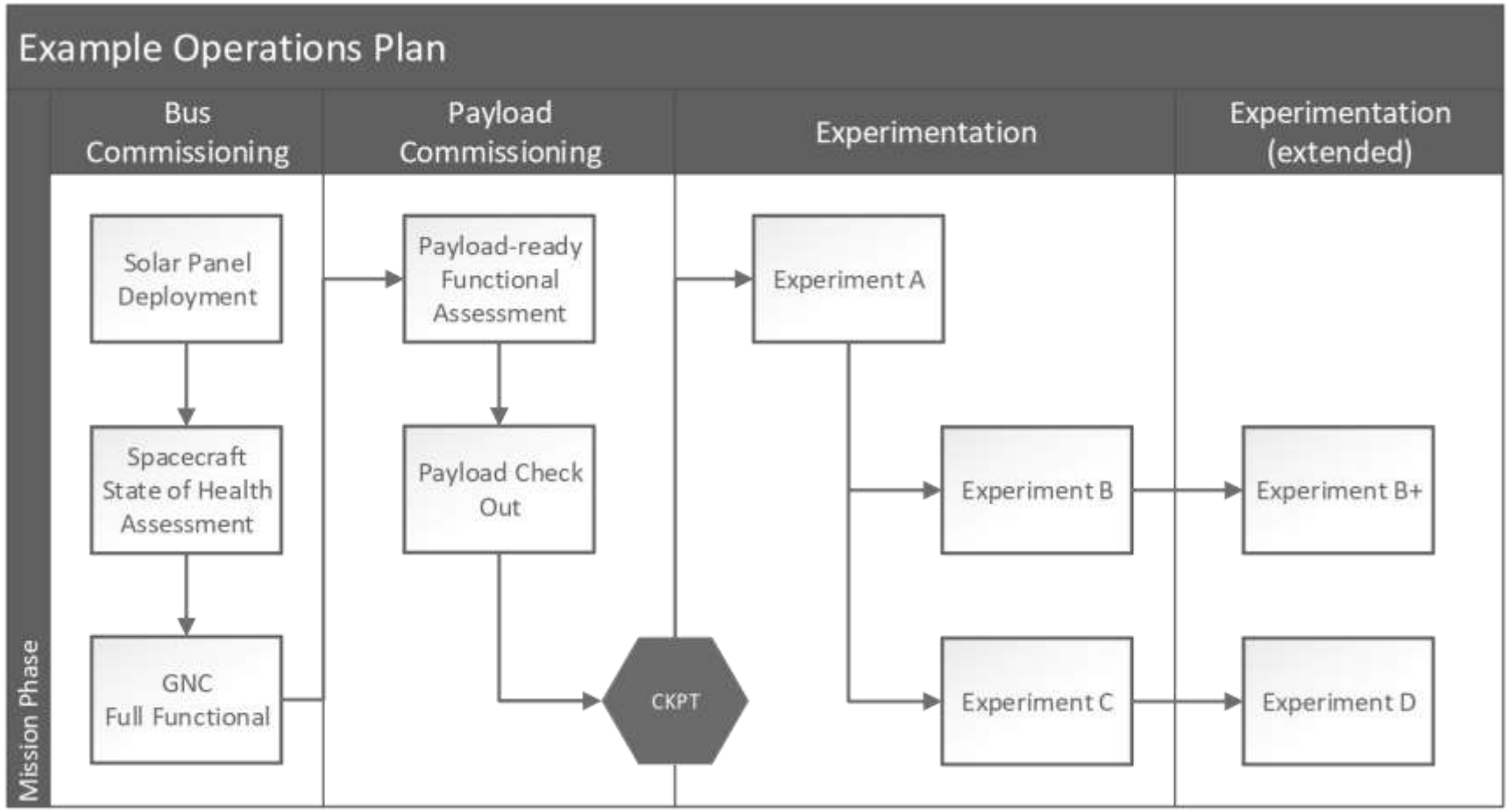
Mission Design	Mission Timeline	Vehicle State transitions and fault handling
• Tasking, Scheduling, & Control • Budget considerations • Drives spacecraft & ground integrated system design / communications architecture	• Identification of success points • Prioritization of objectives and actions • Describe flow and decision points	• Definition of vehicle modes (informs budget and software) • Identifies some levels of fault handling • Identifies vehicle/operator touch points

CONOPS Elements

Mission Timeline

- Identification of success points
- Prioritization of objectives and actions
- Describe flow and decision points

Mission Timeline / Flow Chart



CONOPS - Mission Life

This chart is okay.

However, it **cannot** be the only CONOPS you have!

People will often want to know your predicted duration for a given phase. It's fine to guess but remember that most phase transitions are criteria based!

Launch

RF Silence
~1 Hour

Detumble
~4 Hours

Checkouts
~1 Week

Optics Checkouts
~1 Week

Nominal Ops
~1 Year

Downlink/Uplink

End of Life
~5 Years

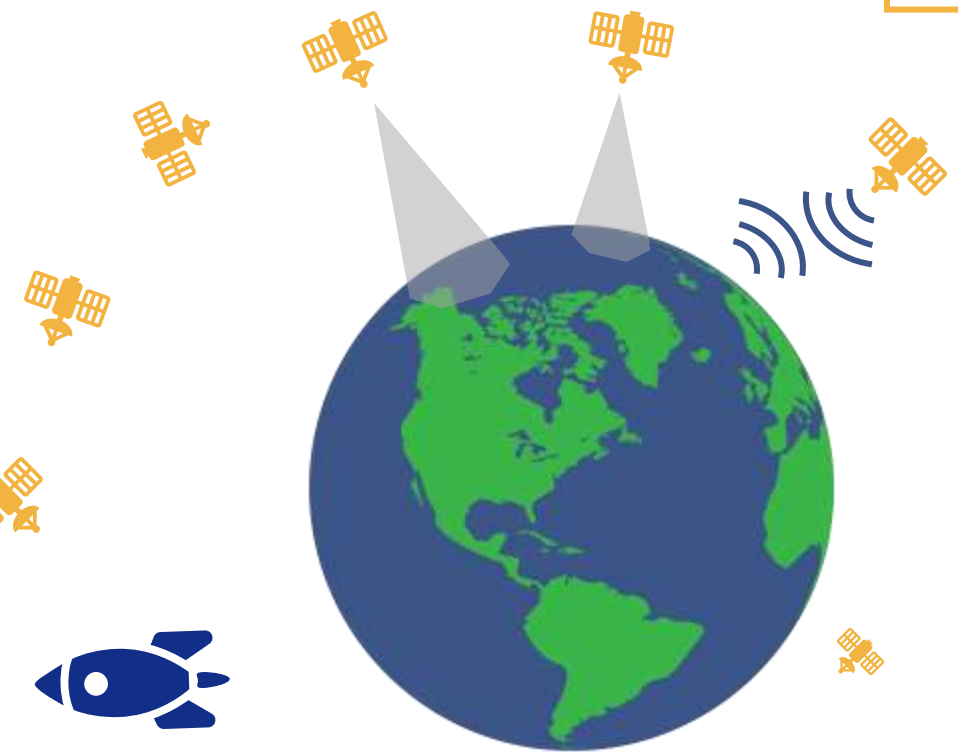


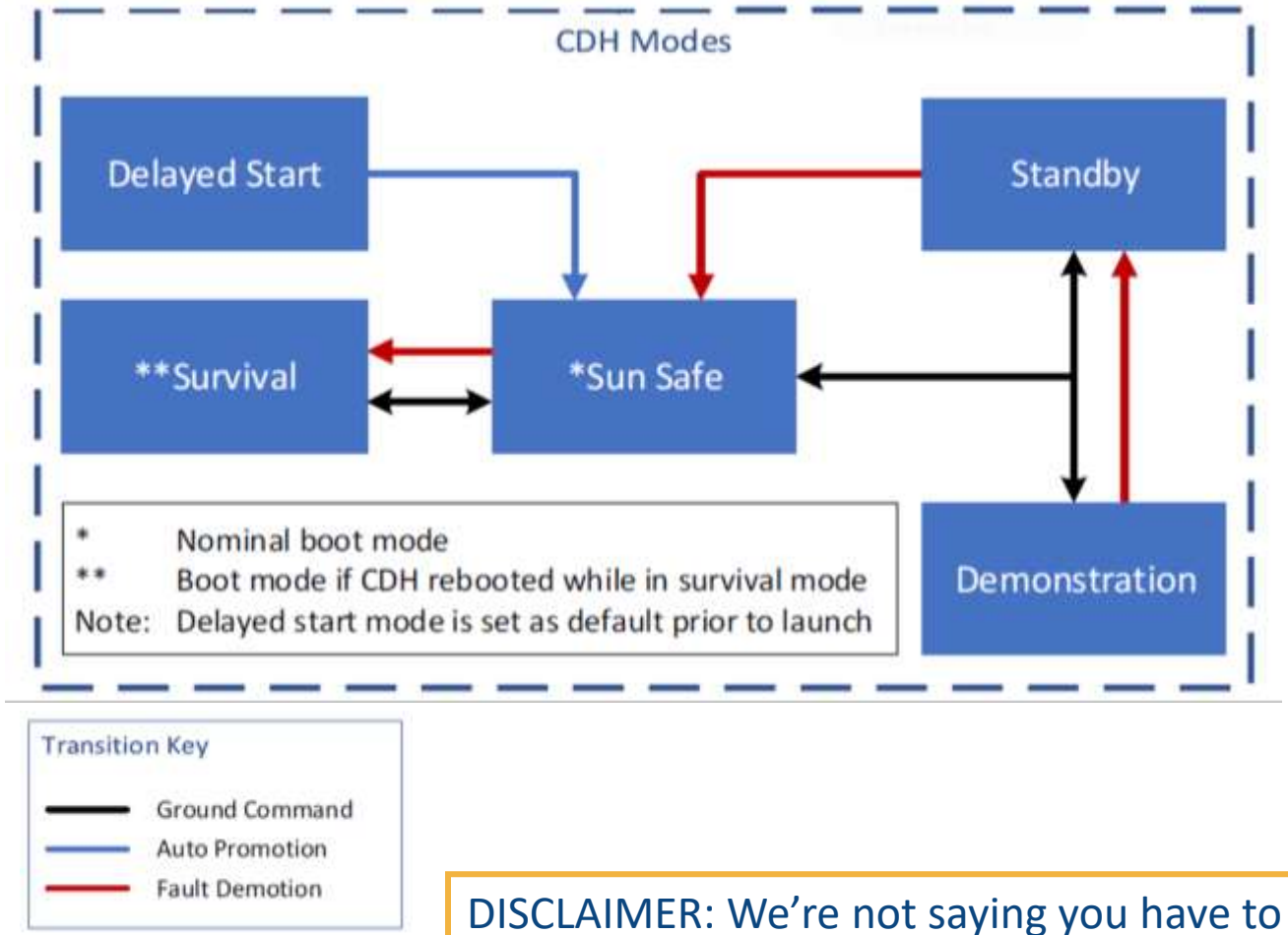
Image Credits:
- Northropgrumman.com
- Videoblocks.com
- isispace.com
- Picsart.com

CONOPS Elements

Vehicle State Transitions and Fault Handling

- Definition of vehicle modes (informs budget and software)
- Identifies some levels of fault handling
- Identifies vehicle/operator touch points

CONOPS Vehicle State



Vehicle State Transitions and Fault Handling

- Definition of vehicle modes (informs budget and software)
- Identifies some levels of fault handling
- Identifies vehicle/operator touch points

DISCLAIMER: We're not saying you have to do modes this way!!

CONOPS Mode Best Practices

Safe Mode

- Have a mode that is “safe”
- You can call it whatever you want
- You want a mode that the satellite can hang out in for indefinite periods of time

Recovery Tree

- Graceful mode degradation is good!
- Consider what mode the spacecraft comes back up in post-reset
- Make sure you have data at the ground to help you debug!
  - I.e. never turn your radio all the way off for power’s sake

Mode Transitions

- Be very thoughtful
- Clearly identify what is an automatic mode transition (fault or auto-promote)
- Fault triggered mode transitions can be good, but be careful with them

CONOPS – Example Experiment A Single Snapshot

Experiment A CONOPS Description

- *Satellite is in operational mode*
- *Operator schedules data collect for selected target*
- *Vehicle does data collect for specific target*
- *Data downlink to ground station*

CONOPS – Example Experiment A
Single Snapshot

Experiment A CONOPS Description

- *Satellite is in operational mode*
- *Operator schedules data collect for selected target*
- *Vehicle does data collect for specific target*
- *Data downlink to ground station*

<u>Experiment Objectives:</u>

- Experiment Collect
- Experiment Data Downlink

<u>Desired Data Product:</u>

- Single pass data collect w/time stamp
- GPS correlated

CONOPS – Example Experiment A Single Snapshot

Experiment A CONOPS Description

- *Satellite is in operational mode*
- *Operator schedules data collect for selected target*
- *Vehicle does data collect for specific target*
- *Data downlink to ground station*

Experiment Entrance Criteria	Experiment Exit Criteria
Vehicle is in a healthy* state	All experiment data is downlinked
Desired Target is identified	Schedule is executed, complete
Vehicle is in operations mode	Fault scenarios -> safe mode

Experiment Objectives:

- Experiment Collect
- Experiment Data Downlink

Desired Data Product:

- Single pass data collect w/time stamp
- GPS correlated

CONOPS – Example Experiment A Single Snapshot

Experiment A CONOPS Description

- *Satellite is in operational mode*
- *Operator schedules data collect for selected target*
- *Vehicle does data collect for specific target*
- *Data downlink to ground station*

Experiment Entrance Criteria	Experiment Exit Criteria
Vehicle is in a healthy* state	All experiment data is downlinked
Desired Target is identified	Schedule is executed, complete
Vehicle is in operations mode	Fault scenarios -> safe mode

Experiment Objectives:

- Experiment Collect
- Experiment Data Downlink

Desired Data Product:

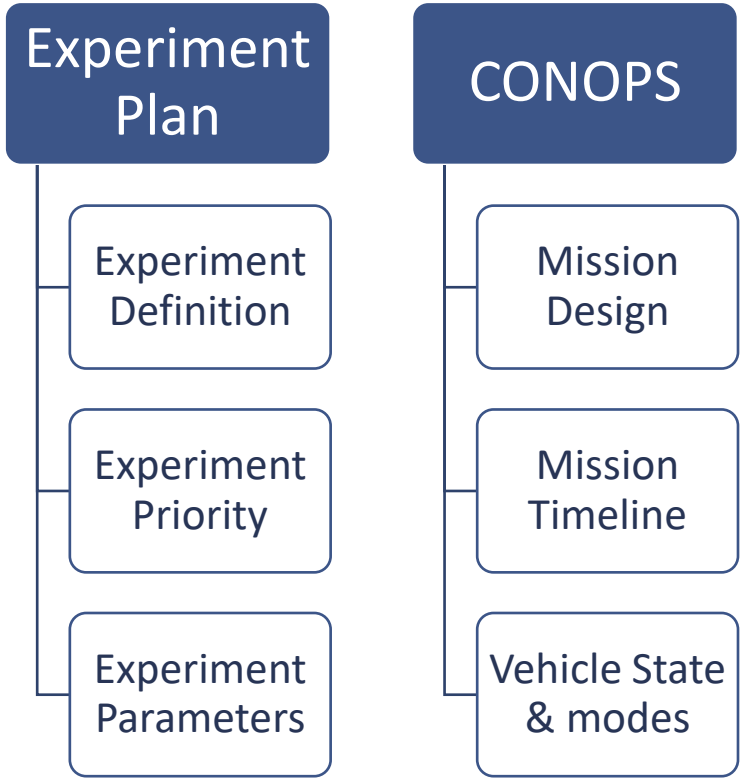
- Single pass data collect w/time stamp
- GPS correlated

Operational Mode State				
Subsystem	Power State	State	Data Type	Data resolution
EPS	ON		Telemetry	1 Hz
CDH	ON		System state	1 Hz
TT&C	ON		Telemetry	1 Hz
ADCS	ON	Fine point	Telemetry	1 Hz
GPS	ON		Telemetry	1 Hz
Payload	ON		Telemetry & Mission data	10 Hz

CONOPS Inform

- System budgets
- Subsystem requirements
- Component selection
- Communication architecture
- Ground system trades

Summary



These documents and concepts are tools to:

- Iterate on your objectives
- Communicate with stakeholders
- Communicate with the team
- Communicate across generations of team
- Develop design guidance & requirements

The Experiment Plan and CONOPS will be as useful as you make it!

Self Assessment: Experiment Plan

- Does your Experiment Plan meet these needs? At each milestone, the plan should tell you what you need to know:

SCR
- Are your objectives achievable?
- Is the mission achievable on a small sat?
- Do your stakeholders understand what you're doing?

SRR
- Do you have the plan well enough understood to know your requirements?
- What about lower level requirements?

PDR/CDR
- Is your design able to achieve the plan?
- What is tradeable?

AI&T
- Does your ground testing support your plan?

Operations
- Informs your weekly planning

There are probably more questions, but this is a start!

Self Assessment: CONOPS

- Does your CONOPS meet these needs? At each milestone, the CONOPS should be able to identify what you need to know:

SCR	SRR	PDR	CDR	AI&T	Operations
Can your mission actually be done?	Do you understand your system requirements?	Does your basic software design work (mode definitions)?	Is thermal a problem?	DAY IN THE LIFE	Informs your operational requirements
	What about lower level requirements?	Do system budgets close with the CONOPS?	Do your budgets close?	Can you still achieve the CONOP based on test results?	Informs your operations planning
		How long will the mission take?	How long will it take to do an experiment?	Will you survive the CONOPS?	Informs progress/criteria gates