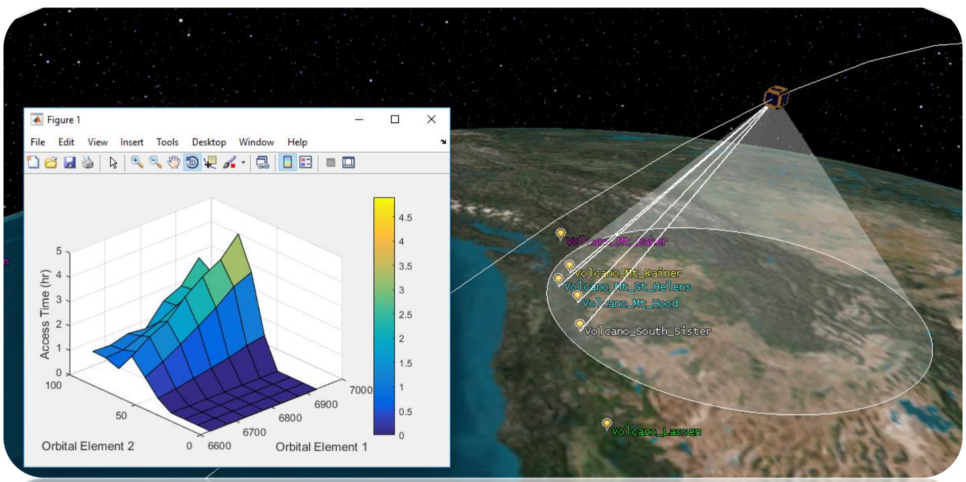
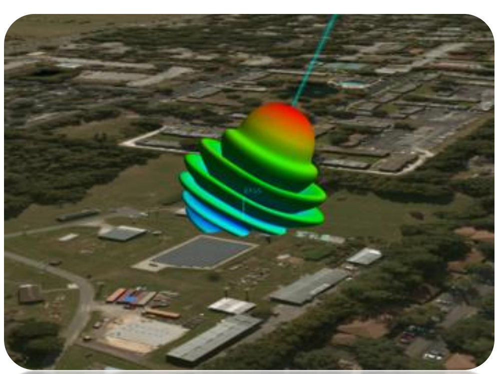
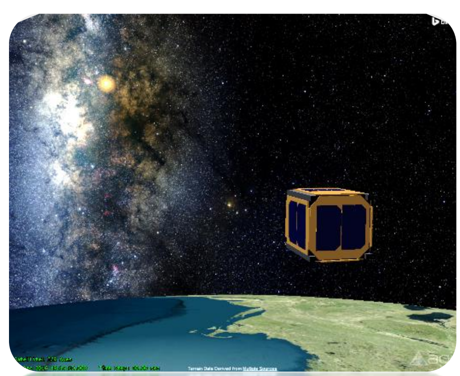
STK CubeSat Lab Manual

Analytical Graphics, Inc.







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Series Overview

Objective and Scope

Objective

The objective of this series is to provide a set of learning laboratories that explore the design of the various aspects of a typical CubeSat mission utilizing AGI's Systems Tool Kit (STK) while following a systems engineering approach to design.

Scope

- This series does not cover every possible aspect or detail of a CubeSat mission design.
- This series presents an ideal CubeSat mission design. Typically, there are many idealities involved in CubeSat missions and they are lessons in compromise.
- The lectures and laboratories in this series are based on the example mission described in this document and in Lesson 0 – Series Overview.
- This series almost exclusively uses STK to demonstrate design principles and processes.

The Systems Engineering Approach

A commonly used model of the systems engineering is the "V-Model". This model describes the iterative process of design starting with definition, continuing through implementation, and iterating during verification and validation. A visual representation of this model is shown in Figure 1.

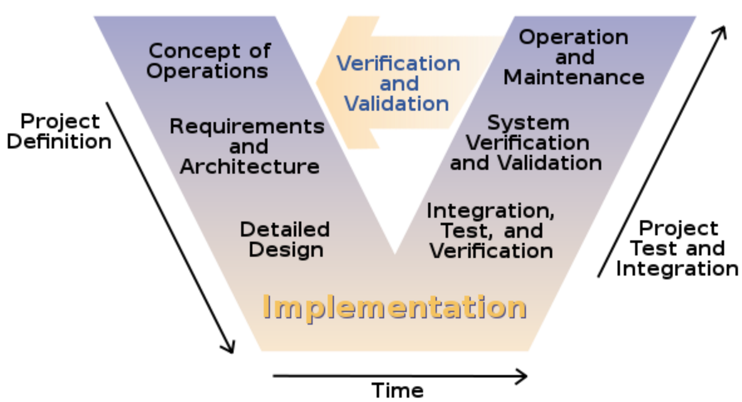


Figure 1 - Visual Representation of the "V-Model"

AGI's Systems Tool Kit (STK) can be used in each phase of this systems engineering process. This series will primarily explore the *project definition* phase of the process. Following the systems engineering design process establishes traceability, documentation, and results in a better, more robust product in the end.

Example Mission Overview

Introduction

You and your team at *AGI University - Exton* want to design, develop, implement, and launch a 1U CubeSat called *STKSat* to characterize the steam, ash and lava emissions of active volcanoes.

STKSat will utilize a new imaging technology capable of detecting these volcanic emissions that will fit within a 0.25 U volume.

Due to the fact that CubeSats are secondary payloads and have little flexibility in orbit selection, you and the team are constrained to a typical CubeSat orbit with an inclination between 0 and 90 degrees and an altitude between 250 and 550 km.

AGI has offered to let you use their ground station at their headquarters in Exton, PA to monitor and command your mission.

Mission Objective

Following the systems engineering process, we establish out *mission objectives, concept of operations, mission requirements,* and *plan for detailed design*.

The objective of *STKSat* is to image active volcanoes in the USA to provide early indications of volcanic eruption. The imager on STKSat will take panchromatic and multispectral images of steam emissions, airborne ash, and lava flows of active volcanoes. These images will enhance current volcanic detection systems.

Concept of Operations (CONOPS)

The concept of operations is an overview of the different modes of the *STKSat* mission. Table 1 describes each of the modes.

Table 1 – Description of *STKSat*'s Operational Modes

Mode	Description
Launch	The launch of the mission and the deployment from the P-POD.
Safe Hold	*STKSat* is in a holding state where it simply beacons health data to the ground station.
Imaging	*STKSat* performs imaging operations of active volcanoes. This is the "science mode".

Downlink	*STKSat* downlinks its stored imagery and sensor data to the ground station.
Retirement	The end of *STKSat*'s life.

A visual representation of *STKSat*'s CONOPS is shown in Figure 2.

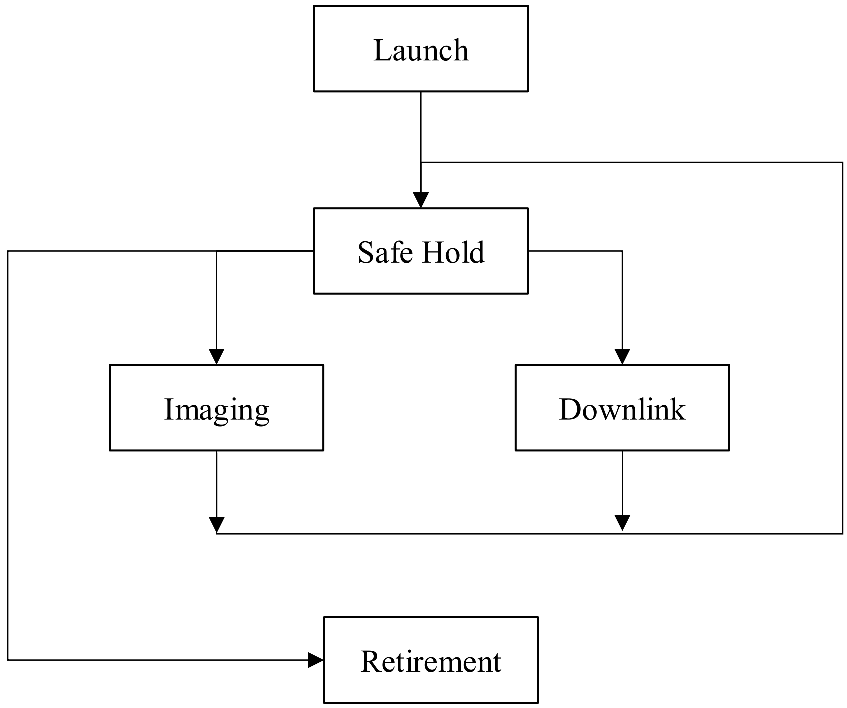


Figure 2 – Visual Representation of *STKSat* Concept of Operations

Mission Requirements

Based on the mission objective and the concept of operations, a set of top-level mission requirements is established for the *STKSat* mission. The requirements are as follows:

1. STKSat shall operate in an orbit that passes over the USA's recently active volcanoes.
2. STKSat shall generate and store the required amount of power to *continuously* operate in orbit.
3. STKSat shall communicate with the ground station via UHF/VHF amateur bands.
4. STKSat shall downlink the spacecraft health to the ground station at a regular interval.
5. STKSat shall respond to and execute all valid uplink from the ground station.
6. STKSat shall maintain nadir pointing of its imager to capture active volcanoes.

Series Structure

The STK CubeSat Lab manual is split into a set of three laboratories. Each laboratory covers a different aspect of the CubeSat mission design process.

Each laboratory consists of a lesson in PowerPoint form, a student laboratory in PDF form in this document, and an instructor version of the laboratory in PDF form with the numerical answers. The laboratories also include VDF (STK Viewer files) for each of the scenarios used in the lessons and laboratories. The lessons in each laboratory present some of the basic concepts used in the laboratory laboratories.

The modular structure of the STK CubeSat Lab is as follows:

- **Laboratory 0 – Series Overview *(Estimated Time: 0.5 - 1 hours)***
  - Lessons / Lesson 0 – Series Overview.pptx

- **Laboratory 1 – Orbit Design *(Estimated Time: 1 - 2 hours)***
  - Lessons / Lesson 1 – Orbit Design.pptx
  - Supporting Material / Laboratory 1 – Orbit Design
  - Topics:
    - Circular and Elliptical Orbits
    - Access Times
    - Launch Providers

- **Laboratory 2 – Solar and Power Design *(Estimated Time: 1 - 2 hours)***
  - Lessons / Lesson 2 – Solar and Power Design.pptx
  - Supporting Material / Laboratory 2 – Solar and Power Design
  - Topics:
    - Solar Panel Setup
    - Power Generation Calculation
    - Power Consumption Calculation

- **Laboratory 3 – Communications Design *(Estimated Time: 2 - 3 hours)***
  - Lessons / Lesson 3 – Communications Design.pptx
  - Supporting Material / Laboratory 3 – Orbit Design
  - Topics:
    - Ground Stations and Spacecraft
    - Antennas and Radiation Patterns
    - Link Budgets and Margins
    - Environmental Losses

Laboratory 1: Orbit Design

Laboratory Overview

Design a circular and an elliptical orbit for STKSat which will provide the most observation times to the USA's recently active volcanos. After determining ideal orbits, non-ideal orbits will be considered due to limitations on available launch providers.

Requirements

- To lessen computation time, use this Scenario Interval:
  - Start: 1 Jan 2024 00:00:00.000 UTCG   Stop: 15 Jan 2024 00:00:00.000 UTCG
- Volcanoes of interest (observations must be obtained at least once to every volcano)
  - Mount St. Helens is located at 46.20 N, 122.18 W
  - Mount Hood is located at 45.37 N, 121.69 W
  - Mount Baker is located at 48.78 N, 121.81 W
  - Mount Rainer is located at 46.85 N, 121.76 W
  - Shishaldin is located at 54.76 N, 163.97 W
  - Mount Cleveland is located at 52.82 N, 169.94 W
  - Fourpeaked located at 58.77 N 153.67 W
  - Kasatochi Island is located at 52.18 N, 175.50 W
  - South Sister is located at 44.10 N, 121.77 W
  - Lassen is located at 40.49 N, 121.51 W
- Altitude of perigee should aim to be greater than 250 km due to drag effects
- Altitude of apogee should aim to be lower than 550 km due to imaging resolution
- Inclination is constrained to be within 0 to 90 degrees
- The imager on STKSat can be pointed within an 80-degree cone field of view relative to nadir by using reaction wheels.
- STKSat will be launched as a secondary payload from one of three launch providers.
- Only account for first order secular differences in earth's oblateness.

Assumptions

- For the circular and elliptical orbit design assume the orbit can be achieved.
- Ignore solar pressure radiation, atmospheric effects, lunar gravitational effects, and higher order earth oblateness effects.
- Orbital Elements can only be known within:
  - 1 degree
  - 1 km
  - 4 decimal places for eccentricity
- Right Ascension of the Ascending Node (RAAN) and true anomaly will always be assumed to be 0 deg because changing these orbital elements will have marginal effects on a longer time period.

- Remember RAAN is defined from Earth's Inertial Axes and the satellites initial placement. Earth's rotation will constantly change the satellites longitude.
- Orbital Period are a few hours for LEOs, thus access time can only vary by a few hours based off of a specific true anomaly.

Deliverables

- Orbital elements and access time for an optimized circular orbit.
- Orbital elements and access time for an optimized elliptical orbit.
- As a percentage, how much more (or less) observation time does the elliptical orbit have compared to the circular orbit?
- With the three launch provider options, which provides the most observation time?
- How much observation time is provided with the best launch provider?

Table 2 - Laboratory 1 Deliverables

Deliverable	Answer
Deliverable 1: *Propagator*	
Deliverable 2: *Circular Orbit*	
Deliverable 3: *Elliptical Orbit*	
Deliverable 4: *Observation Time*	
Deliverable 5: *Launch Provider*	

Section 1: Problem Setup in STK

The first step is to create a scenario and to insert STKSat and the volcanoes.

1. Create a new scenario and name it **OrbitDesignLab**
2. Add the specified start and stop times:
    a. Start: 1 Jan 2024 00:00:00.000 UTCG
    b. Start: 15 Jan 2024 00:00:00.000 UTCG

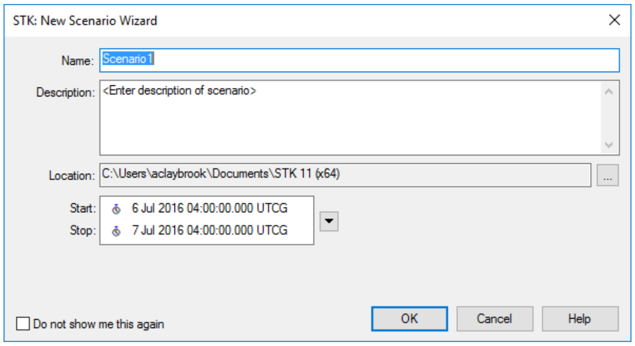


Figure 3 - Laboratory 1 Scenario Setup

3. Click OK to create the scenario.
4. Click the Save button in the top left corner.
5. Go to the top toolbar, click **Insert** then in the dropdown click **New.**

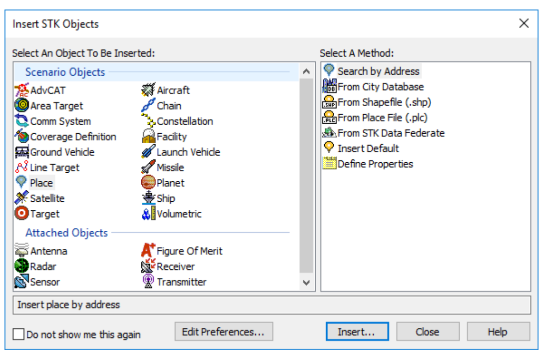


Figure 4 - Inserting an STK Object

6. Select **Place** ( ) and select the method as **Insert Default**. Click **Insert…**
7. From the Insert STK Objects window select **Satellite** and the method as **Orbit Wizard**. Click **Insert…**
8. Rename the satellite **STKSat** ( ) then click **OK** to accept the other defaults.
9. Right click on **STKSat** in the Object Browser then click **Properties** ( ).
10. Here various properties of the satellite can be changed by navigating through different tabs on the left. For now, select the propagator described below in Deliverable 1. After selecting the propagator, it can be changed in the drop down menu at the top of the page. Then click **OK**.

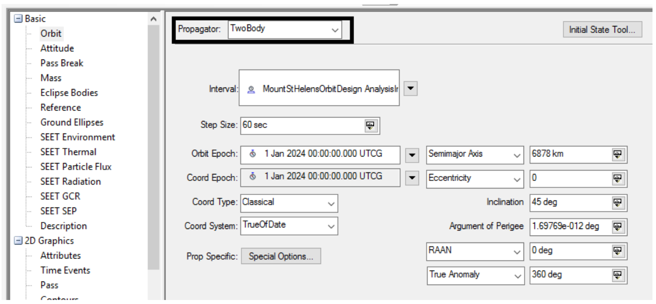
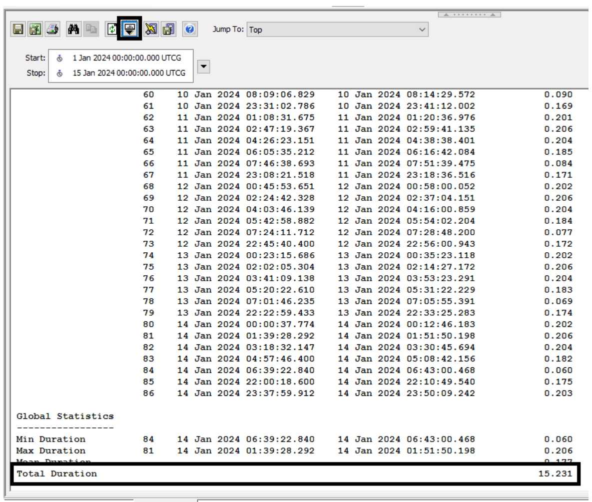


Figure 5 - Changing the Orbit Propagator

Deliverable 1: Chose a propagator that will account for first order earth oblateness effects while ignoring drag, solar pressure, lunar gravitational effects, and higher order earth oblateness effects. For more information on propagators visit http://help.agi.com/stk/#stk/vehSat_orbitProp_choose.htm?Highlight=propagators

11. Rename the **Place** to **Mt_St_Helens** by right clicking on it in the object browser and selecting **Rename** in the drop down. Pressing **F2** with **Place** selected is another approach.
12. Open **Mt_St_Helens** properties, change the latitude to 46.20 longitude to -122.18. The altitude will automatically be set to be on the terrain surface. Click **OK.**
13. Right click on **Mount_St_Helens** then click **Zoom To**. Zoom out until the **STKSat** is visible.
14. Right click on **STKSat** in the object browser then click **Access**. Ensure **Mount_St_Helens** is selected as the object access is being computed to, then click **Access** under Reports.
15. An access report is generated with times in which **STKSat** has line of sight access to **Mount_St_Helens.** Scroll to the bottom of the report to see the Total Duration; this is the total access **STKSat** has to Mount St. Helens throughout the entire scenario interval.
16. To change the units, click on the **Report Units** (icon) icon at the top of the report. Change the time units from seconds to hours. The access report should look similar to the one below. Right now the total duration is about 15 hours.



Jump To: Top
Start: 1 Jan 2024 00:00:00.000 UTCG
Stop: 15 Jan 2024 00:00:00.000 UTCG

	60	10 Jan 2024 08:09:06.829	10 Jan 2024 08:14:29.572	0.090
	61	10 Jan 2024 23:31:02.786	10 Jan 2024 23:41:12.002	0.169
	62	11 Jan 2024 01:08:31.675	11 Jan 2024 01:20:36.976	0.201
	63	11 Jan 2024 02:47:19.367	11 Jan 2024 02:59:41.135	0.206
	64	11 Jan 2024 04:26:23.151	11 Jan 2024 04:38:38.401	0.204
	65	11 Jan 2024 06:05:35.212	11 Jan 2024 06:16:42.084	0.185
	66	11 Jan 2024 07:46:38.693	11 Jan 2024 07:51:39.475	0.084
	67	11 Jan 2024 23:08:21.518	11 Jan 2024 23:18:36.516	0.171
	68	12 Jan 2024 00:45:53.651	12 Jan 2024 00:58:00.052	0.202
	69	12 Jan 2024 02:24:42.328	12 Jan 2024 02:37:04.151	0.206
	70	12 Jan 2024 04:03:46.139	12 Jan 2024 04:16:00.859	0.204
	71	12 Jan 2024 05:42:58.882	12 Jan 2024 05:54:02.204	0.184
	72	12 Jan 2024 07:24:11.712	12 Jan 2024 07:28:48.200	0.077
	73	12 Jan 2024 22:45:40.400	12 Jan 2024 22:56:00.943	0.172
	74	13 Jan 2024 00:23:15.686	13 Jan 2024 00:35:23.118	0.202
	75	13 Jan 2024 02:02:05.304	13 Jan 2024 02:14:27.172	0.206
	76	13 Jan 2024 03:41:09.138	13 Jan 2024 03:53:23.291	0.204
	77	13 Jan 2024 05:20:22.610	13 Jan 2024 05:31:22.229	0.183
	78	13 Jan 2024 07:01:46.235	13 Jan 2024 07:05:55.391	0.069
	79	13 Jan 2024 22:22:59.433	13 Jan 2024 22:33:25.283	0.174
	80	14 Jan 2024 00:00:37.774	14 Jan 2024 00:12:46.183	0.202
	81	14 Jan 2024 01:39:28.292	14 Jan 2024 01:51:50.198	0.206
	82	14 Jan 2024 03:18:32.147	14 Jan 2024 03:30:45.694	0.204
	83	14 Jan 2024 04:57:46.400	14 Jan 2024 05:08:42.156	0.182
	84	14 Jan 2024 06:39:22.840	14 Jan 2024 06:43:00.468	0.060
	85	14 Jan 2024 22:00:18.600	14 Jan 2024 22:10:49.540	0.175
	86	14 Jan 2024 23:37:59.912	14 Jan 2024 23:50:09.242	0.203

Global Statistics

Min Duration	84	14 Jan 2024 06:39:22.840	14 Jan 2024 06:43:00.468	0.060
Max Duration	81	14 Jan 2024 01:39:28.292	14 Jan 2024 01:51:50.198	0.206
Total Duration				15.231

Figure 6 - Access Report

17. Close the access report and now a line should be visible between **STKSat** and **Mt_St_Helens** showing access. Animate through the scenario to watch the access times. For an earth inertial view click the **Home View** () icon in the 3D Graphics window.
18. **Save** your scenario. When saving scenarios, only save one scenario per folder.
19. The next section will utilize MATLAB. If you do not have access to MATLAB skip **Section 2a** and go to **Section 2b: Using STK.**

Section 2a: Utilizing MATLAB for STK Automation

In the absence of STK Analyzer, MATLAB will be utilized to provide an iterative approach to optimize STKSat's orbit for the most access time to a list of volcanoes. The provided script will setup the problem in STK, so the scenario created in Problem Setup in STK will not be used if you are using MATLAB.

Familiarization with MATLAB Integration

1. Download and open the **Lab1OrbitDesign.m** file in MATLAB.
2. **Lab1OrbitDesign.m** sets up the scenario in STK.
3. The MATLAB script is divided up into sections denoted by the double percent signs `%%`
4. The sections do the following:
    a. Clears the Workspace and Command Window
    b. Launches STK
    c. Defines the scenario's start and stop time
    d. Creates a place for each volcano
    e. Creates a constellation of **Volcanoes**
    f. Creates a satellite called **STKSat**
    g. Creates a chain between **STKSat** and **Volcanoes**
    h. Allows the user to vary orbital elements to maximize access time
5. As the user you must input the following:
    a. STKSat's orbital elements
    b. Number of orbital elements to vary at once
    c. Which orbital elements to vary and their ranges
6. The section of the code you can **INPUT** is segmented by the asterisks (*).
7. Before running the code review the **READ ME** comments. Click **Run** ().

8. STK should open up with a few new types of objects: places, a sensor, a constellation and a chain.
    a. The remaining volcanoes of interest have been inserted.
    b. A sensor attached to STKSat, which represents the imagers field of view.
    c. A constellation is simply a group of objects. These object can be assigned in the constellation's properties.
    d. A chain is a link, such as line of sight access, between two or more objects.

Guided Trade Study with MATLAB

This section will walk through how to design an optimal circular and elliptical orbit for STKSat.

1. Define the orbital elements for the lowest altitude circular orbit allowed.
    a. For the given design constraints and a circular orbit:
        i. Eccentricity (e) = 0
        ii. Argument of Perigee (AoP) = 0 (Arbitrary for a circular orbit)
        iii. Right-hand Ascension of the Ascending Node (RAAN) = 0
        iv. True Anomaly (TA) = 0
    b. Which leaves two elements to vary:
        i. Semi-major Axis (a)
        ii. Inclination (i)
2. Scroll to the asterisk section of the script.
3. Set the semi-major axis to **6628** km for the lowest altitude.
4. Set the inclination to **0** degrees as an initial guess.
5. Select **2** as the NumberToVary.
6. Change:
    a. Element1 to **‘a’**
    b. Element1Min to **6628**
    c. Element1Max to **6928**
    d. StepSize1 to **100**
    e. Element2 to **‘i’**
    f. Element2Min to **0**
    g. Element2Max to **90**
    h. StepSize2 to **10**

```
%***************************************************************************
%***************************************************************************
% INPUT Orbital Elements
keplerian.SizeShape.SemiMajorAxis = 6628; %SemiMajorAxis(km): >6378.14
keplerian.SizeShape.Eccentricity = 0; %Eccentricity: 0 to 0.99999
keplerian.Orientation.Inclination = 0; %Inclination: 0 to 180 *NOTE* Values
keplerian.Orientation.ArgOfPerigee = 0; %Argument of Periapsis: 0 to 360
keplerian.Orientation.AscNode.Value = 0; %Righthand Ascention of the Ascend
keplerian.Location.Value = 0; %True Anomaly: 0 to 360

% INPUT Number of Orbital Elements to Vary
NumberToVary = 0; %0, 1, or 2

% INPUT Which Orbital Element(s) to Vary and the Range(s)
Element1 = 'a'; %First Orbital Element: 'a','e','i','AoP','RAAN',or 'TA'
Element1Min = 6378; %First Orbital Element Minimum
Element1Max = 7378; %First Orbital Element Maximum
StepSize1 =100; %First Orbital Element Step Size

% INPUT ONLY USED if Using 2 Orbitial Elementsl
Element2 = 'i'; %Second Orbital Element: 'a','e','i','AoP','RAAN',or 'TA'
Element2Min = 0; %Second Orbital Element Minimum
Element2Max = 180; %Second Orbital Element Maximum
StepSize2 = 45; %Second Orbital Element Step Size
%***************************************************************************
%***************************************************************************
```

Figure 7 - MATLAB Script

7. With STK visible click **Run Section**. Watch as the orbit is changed within STK. The number of iterations and percent complete is displayed in the command window.
8. Observe the surface plot that appears when the analysis is complete. And notice any trends with increasing semi-major axis and inclination. The graph below is just an example.

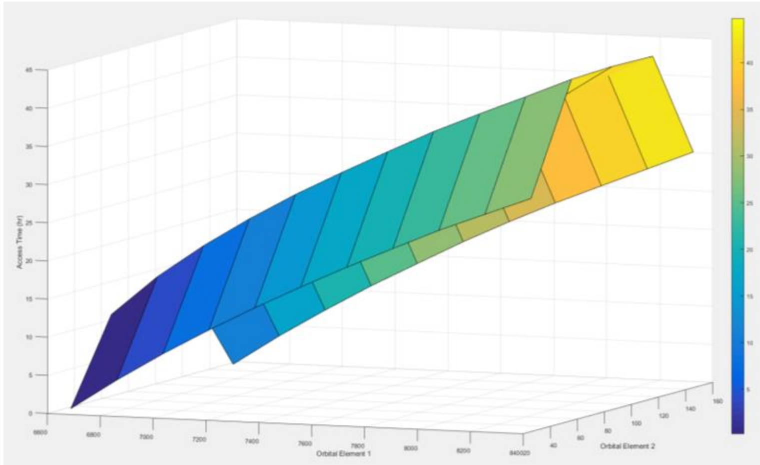


Figure 8 - Semi-Major Axis vs. Inclination Graph

9. Change **NumberToVary** to **1**. Change inclination in the INPUT Orbital Elements section to the highest value displayed in your command window. You do not have to update semi-major axis because it will be varied again with greater precision.
10. Set the minimum and maximum value of the semi-major axis to be a 100 km range which includes the semi-major axis with the maximum access time from the previous run. Do not exceed the maximum altitude of 550 km (6928 km). Change StepSize1 to 10. Click **Run Section** ( ).
11. Observe the corresponding semi major axis with the highest duration from the plot.
12. Update the range to be within 10 km of the best semi-major axis with a step size of 1 km. Click **Run Section.**
13. Once the optimal semi-major axis value is found insert this value into the INPUT section. Now vary inclination in a similar fashion to reach the optimal value. Remember that orbital elements can only be known to within 1 degree or kilometer.
14. Check with your instructor to ensure your semi-major axis, inclination and max access time are correct before moving on to the elliptical orbit. Record the orbital elements and access time.

Deliverable 2: What are the orbital elements for the circular orbit which correspond to the most access time? What is the maximum access time?

15. Now let's observe the effects of eccentricity. Assume the most eccentric orbit allowed, where eccentricity is calculated from $e = (r_a - r_p)/(r_a + r_p)$. r_a is the radius of apogee determined from the highest allowed altitude and r_p is the radius of perigee determined from the lowest allowed altitude.
16. Input this eccentricity value. However, when eccentricity is changed the semi major axis must be readjusted and calculated from $a=(r_a+r_p)/2$ to stay within the altitude bounds. Input the new semi major axis.
17. Now vary the argument of perigee from 0 to 360 in steps of 10 and click **Run Section**. Then refine your results to a smaller range with a step of 1. Click **Run Section**.

18. Lastly check to see if a combination of slightly different inclinations and argument of perigee results in better observation time. Try varying inclination ± 2 degrees from the found value and argument of perigee ± 5 degrees. Both with a step size of 1 deg.

    Deliverable 3: What are the orbital elements for the elliptical orbit which correspond to the most access time? What is the maximum access time?

19. With the final orbital elements selected compare the eccentric orbit to the circular orbit.

    Deliverable 4: Does the elliptical orbit have more observation time than the circular orbit? If so, by how much (as a percentage)?

20. Skip Section 2b.

Section 2b: Using STK

Without MATLAB, optimal orbits can still be achieved by manually adjusting the orbital elements over a carefully selected range.

Finishing the Problem Set up with STK

1. Go to the Insert STK Object window.
2. Add a default **sensor** ( ) to STKSat and name it **Imager**.
3. Add the remaining volcanoes into STK manually. Go to the Insert STK Objects window, select Place, and select the Search by Address method. Click **Insert…** in the following window enter the volcano names below and insert them into STK.
    a. Mount Hood, OR
    b. Mount Baker, WA
    c. Mount Rainer, WA
    d. Shishaldin Volcano, AK
    e. Mount Cleveland, AK
    f. Fourpeaked Mountain, AK
    g. Kasatochi Island, AK
    h. Lassen Peak, CA (Pick the first option.)
    i. Middle Sister, OR (Pick the first option, this is actually South Sister.)
4. For consistent results adjust the **Properties** of each volcano to match the latitude and longitude given in the **Requirements**.
5. Add a **constellation** ( ) and name it **Volcanoes**. In **Volcanoes** properties move all of the volcanoes in the scenario to the right into the assigned section.
6. Add a **chain** ( ) named **Observe**. In its properties move **Imager** to the assigned objects section, then add the constellation object **Volcanoes**.
7. Right click on **Observe**, click on **Report & Graph Manager**. **Generate** the **Complete Chain Access** report. The total duration at the bottom is what we are aiming to maximize.

Guided Trade Study with STK

This section will walk through how to design an optimal circular and elliptical orbit for STKSat.

1. Define the orbital elements for the lowest altitude circular orbit allowed.
    a. For the given design constraints and a circular orbit:
        i. Eccentricity (e) = 0
        ii. Argument of Perigee (AoP) = 0 (Arbitrary for a circular orbit)
        iii. Right-hand Ascension of the Ascending Node (RAAN) = 0
        iv. True Anomaly (TA) = 0
    b. Which leaves two elements to vary:
        i. Semi-major Axis (a)
        ii. Inclination (i)
2. Go to STKSat's properties and change the following, then click **Apply**:
    a. Semimajor Axis = 6628 km
    b. Eccentricity = 0
    c. Inclination = 40 deg
    d. Argument of Perigee = 0 deg
    e. RAAN= 0 deg
    f. True Anomaly = 0 deg

3. By clicking apply the STKSat's properties will be left open which is important for frequently changing orbital elements.
4. Right click on to the **Observe** and go to **Report & Graph Manager**. **Generate** a **Complete Chain Access** report. Leave the report open. Record the Total Duration. For visualization and keeping track of these values, use Excel to record and plot the observation time vs the semi major axis.
5. With the report open, clicking the **Refresh** ( ) button will update the report to any newly applied properties.
6. Increase STKSat's **Semimajor Axis** by 100 km. Then rerun the **Complete Chain Access** report. Record the Total Duration. Do this a 3rd time to reach the highest altitude allowed.
7. With the highest total duration found and the corresponding semi major axis, do the process again by increasing in steps of 10 km over a range of ± 30 km above the highest recorded semimajor axis, but do not exceed the maximum allowed altitude.
8. Then narrow down the range further to ±5 km with a step of 1 km. Use information based off of previous trends to skip unnecessary iterations
9. Redefine your semi major axis to the values which corresponds to the most access time.
10. Now follow a similar process for inclination. Start off with broad jumps between the allowed inclination bounds with steps of around 10 degrees.
11. Then narrow down your down your selection to a 1-degree precision.
12. Check with your instructor to ensure your semi-major axis, inclination and max access time are correct before moving on to the elliptical orbit. Record the orbital elements and access time.

Deliverable 2: What are the orbital elements for the circular orbit which correspond to the most access time? What is the maximum access time?

13. Now let's observe the effects of eccentricity. Assume the most eccentric orbit allowed, where eccentricity is calculated from $e = (r_a-r_p)/ (r_a+r_p)$. Where r_a is the radius of apogee determined from the highest allowed altitude and r_p is the radius of perigee determined from the lowest allowed altitude.
14. Input this eccentricity value. However, when eccentricity is changed the semi major axis must be readjusted and calculated from $a=(r_a+r_p)/2$ to stay within the altitude bounds. Input the new semi major axis.
15. Now vary the argument of perigee from 0 to 360 in steps of 45. To save time think where would apogee be located to provide the most observation time to volcanoes. Record the total durations of access time. Then refine your results to a smaller range with a step of 5 and then to 1 degree.
16. Lastly check to see if a combination of slightly different inclinations and argument of perigee results in better observation time. Try varying inclination ± 2 degrees from the found value and argument of perigee ± 2 degrees. Both with a step size of 1 deg.

    Deliverable 3: What are the orbital elements for the elliptical orbit which correspond to the most access time? What is the maximum access time?

17. With the final orbital elements selected compare the eccentric orbit to the circular orbit.

    Deliverable 4: Does the elliptical orbit have more observation time than the circular orbit? If so, by how much (as a percentage)?

Section 3: Choose a Launch Provider

Although there may be an ideal orbit for STKSat reaching these orbits is often not feasible because dedicated launch vehicles are extremely expensive. Therefore, CubeSats are typically secondary payloads to save on launch costs. STKSat will be a secondary payload on one of the following three launch providers listed below:

- Option 1: ULA launch to a circular polar orbit
    - a= 6800 km
    - I = 90 deg
- Option 2: ATK launch to the ISS (assume circular orbit)
    - a = 6780 km
    - i = 51.6 deg
- Option 3: Space X launch from Cape Canaveral to a circular orbit
    - a = 6928 km
    - i = 28.5 deg

1. Determine the launch provider which will provide the highest access times by updating the orbital elements in MATLAB and by selecting **0** as the NumberToVary.
2. Confirm your answer in STK by right clicking on the chain **Observe** then selecting **Report & Graph Manager. Generate** the **Complete Chain Access** report.
3. Finally confirm your selection with your instructor.

   Deliverable 5: Which launch provider gives the highest access times? What is the access time?

Laboratory 2: Solar and Power Design

Laboratory Overview

This laboratory introduces solar and power design concepts for Cubesat missions. The example STKSat mission from AGI's Educational Alliance Program – CubeSat Mission Design Series will be utilized.

Note: This lab primarily utilizes STK and Microsoft Excel. STK Scheduler can also be used to conduct a solar power system analysis.

Objective

The objective of this laboratory is to:

- Analyze the average solar panel power generation for STKSat over the course of a year.
- Determine the time period of STKSat's greatest power draw and conduct power generation and power consumption analysis.
- Compare power generation and power consumption calculations to select the solar panel/battery combination that best satisfies the mission requirements.

Requirements

1. The solar panel/battery combination must be able to supply at least 0.75W of power to STKSat while it's in a holding state.
2. The solar panel/battery combination must be able to supply at least 6.75W of power to STKSat while it's transmitting data to the ground station.
3. The solar panel/battery combination must be able to supply at least 4W of power to STKSat while it's imaging a volcano/volcanoes.
4. Once battery capacity reaches 100% extra energy must be dissipated as heat.
5. The battery must never fall below its rated DoD.

Assumptions

1. The same solar panel sheet will be used on every side of STKSat excluding the underside which will maintain constant nadir pointing.
2. As this is a 1U CubeSat there will be no deployable solar panels.
3. Since a yearlong scenario analysis is quite extensive, solar data will be gathered on the 15th of each month and will be extrapolated across the entire month.
4. Difference in weight between components is minimal and will not be taken into account.

Constant Power Consumption Values

The following table lists STKSat's subsystems that use a constant power draw:

Table 3 - Constant Power Consumption Values

Sub-System	Power (W)
Spacecraft Computer	.5
Receiver	0.250

Variable Power Consumption Values

The following table lists STKSat's subsystems that use a variable power draw:

Table 4 - Variable Power Subsystems

Sub-System	Power (W)
Transmitter	6 (In use) 0 (Off)
Camera	0.250 (In use) 0 (Off)
Reactions Wheels	3 (In use) 0 (Off)

Possible Solar Panel Selection

The following table lists the possible solar panel options for STKSat. The Power Output value represents the total power output of the system of solar panels, not each panel independently.

Table 5 - Solar Panel Options

Model	Power Output per side (W)	Efficiency	Cost ($)
System 1	2	.28	18,000
System 2	1.5	.21	15,000
System 3	1.2	.168	12,000

Possible Battery Selection

The following table lists the possible battery option for STKSat.

Table 6 - Battery Options

Model	Type	Capacity(Whr)	DoD	Cost ($)
Battery 1	Li-ion	7.5	15%	2,000
Battery 2	Li-ion	10	15%	3,000
Battery 3	Li-ion	15	15%	4,000

Deliverables

Place your answers for all of the laboratory deliverables in Table 7 below, or on a separate sheet provided by your instructor.

Table 7 - Laboratory 2 Deliverables

Deliverable	Answer
Deliverable 1: *Least/Most Power Generation Months*	
Deliverable 2: *Start and Stop Times*	
Deliverable 3: *Solar Panel Selection*	
Deliverable 4: *Battery Selection*	

Section 1: Setting Up the Scenario

In this section you will setup the scenario that will be used for this laboratory. This involves adding the STKSat spacecraft with the orbit determined in Laboratory 1 – Orbit Design, STKSat's camera, and the volcano objects.

Adding the STKSat Satellite

Note: If you have already completed Laboratory 1, change your existing scenario's Start and Stop times to the values in Table 8 below. Then, skip the rest of the step.

1. Open STK () and create a new Scenario () with the following information:

Table 8 - Laboratory 2 Scenario Setup

Field	Value
Name	Laboratory_2_Solar_and_Power_Design
Description	This is the scenario for Laboratory 2 – Solar and Power Design of AGI's Educational Alliance Program CubeSat Mission Design Series.
Location	Leave Default
Start	1 Jan 2024 00:00:00.000 UTCG
Stop	1 Jan 2025 00:00:00.000 UTCG

2. From the Insert menu, select New () to open the Insert STK Objects window.
3. Select the Satellite () object type and select the Define Properties method. Click Insert.
4. Change the Propagator to J2Perturbation.
5. The Satellite's Orbit Epoch will be defaulted to the Analysis Period for the Scenario. We will be changing the Scenario Interval later on to simplify calculations but we want to make sure the Satellite's Orbit Epoch stays consistent.
    a. Change the Orbit Epoch to 1 Jan 2024 00:00:00.000 UTCG.
6. In the Orbital Elements section, enter the information below. These are the orbital elements that should have been obtained in Laboratory 1 – Orbit Design.

Table 9 - Laboratory 2 Orbital Parameters

Orbital Element	Value
Semimajor axis	6780 km
Eccentricity	0
Inclination	51.6 deg
Argument of Perigee	0 deg
RAAN	0 deg
True Anomaly	0 deg

7. Click the Apply button to apply the changes. Then, click OK to close the window. Notice the propagated orbit is now visible in the 2D and 3D Graphics Windows.
8. Change the Satellite Name to "STKSat".

Changing STKSat's Model

1. As we wish to run solar power analysis later on, we will insert a CubeSat model with prebuilt solar panels. Reopen STKSat's properties and click 3D Graphics -> Model. Under Model, click the ellipsis button to the right of Model File. In the popup window (C:\Program Files\AGI\STK 11\STKData\VO\Models\Space) find the file "cubesat_1u.dae" and click to Open it.
2. The default model has identical solar panels on 5 out of the 6 sides. The 6th side has a smaller grouping of panels. We will rotate the model so that the smaller group of panels is on the bottom face giving us room for STKSat's camera.
    a. Go to the 3D Graphics -> Offsets tab.
    b. Select the Use box under Rotation Offset and set the X value to 180 deg.
    c. Click OK to dismiss the Properties window.

Adding STKSat's Camera

Note: If you have already completed Laboratory 1, you can skip this step.

Since there is no camera object within STK you will model the camera using a Sensor object and specify its field of view.

1. From the Insert menu, select New () to open the Insert STK Objects window.
2. Select the Sensor () object and select the Define Properties method. Then, click Insert.
3. In the Select Object window, select STKSat and click OK.
4. In the Sensors Basic – Definition properties change the Cone Half Angle to 40 degrees.
5. Rename the Sensor to "Imager".

Adding a Ground Station Facility

1. In the Insert STK Objects window, select Facility (). Select the Insert Default method. Click the Insert button to insert the Facility.
2. Right-click on the Facility object in the Object Browser and rename it to "Exton".

   Note that when inserting a default Facility, it is placed at the coordinates of AGI's headquarters in Exton, PA. The location of the ground facility will be placed in a nearby field with the following coordinates:

   Latitude: 40.0388 deg
   Longitude: -75.6005 deg

3. Right-click on the Facility object in the Object Browser and click Properties.

4. In the Properties window, browse to the Basic – Position page. Modify the Latitude and Longitude fields to match the coordinates above.
5. Click the Apply button to apply the changes. Then, click the OK button to close the properties window.
6. Right-click on Exton in the Object Browser and select Zoom To. Notice the location of the Facility in a nearby field.

Adding the Volcanoes

Note: If you have already completed Laboratory 1, you can skip this step.

1. In the Insert STK Objects window, select Place, and select the Search by Address method. Click Insert…
2. In the following window enter the volcano names below and insert them into STK.
   - Mount St. Helens, WA
   - Mount Hood, OR
   - Mount Baker, WA
   - Mount Rainer, WA
   - Shishaldin Volcano, AK
   - Mount Cleveland, AK
   - Fourpeaked Mountain, AK
   - Kasatochi Island, AK
   - Middle Sister, OR (pick the first one)
     - Note: This is actually South Sister and is labeled as such in the MATLAB script.
   - Lassen Peak, CA

We will now group these volcanoes into a Constellation object for analysis later on.

3. In the Insert STK Objects window, select Constellation ( ). Select the Define Properties method. Click the Insert button to insert the Constellation.
4. In the left-side Available Objects window hold down the ctrl key and select all of the volcanoes from the list.
5. Click the arrow over button to move all of the volcanoes into the Assigned Objects window.
6. Click the OK button to dismiss the Properties window.

Adding the Chain Object

Note: If you have already completed Laboratory 1, you can skip this step.

1. In the Insert STK Objects window, select Chain ( ). Select the Define Properties method. Click the Insert button to insert the Chain.
2. In the left-side Available Objects window expand STKSat and select Imager. Click the arrow over button to move Imager to the Assigned Objects window.
3. Now click the Constellation object called Volcanoes and move that over to the Assigned Objects as well. Volcanoes should be second in the list.

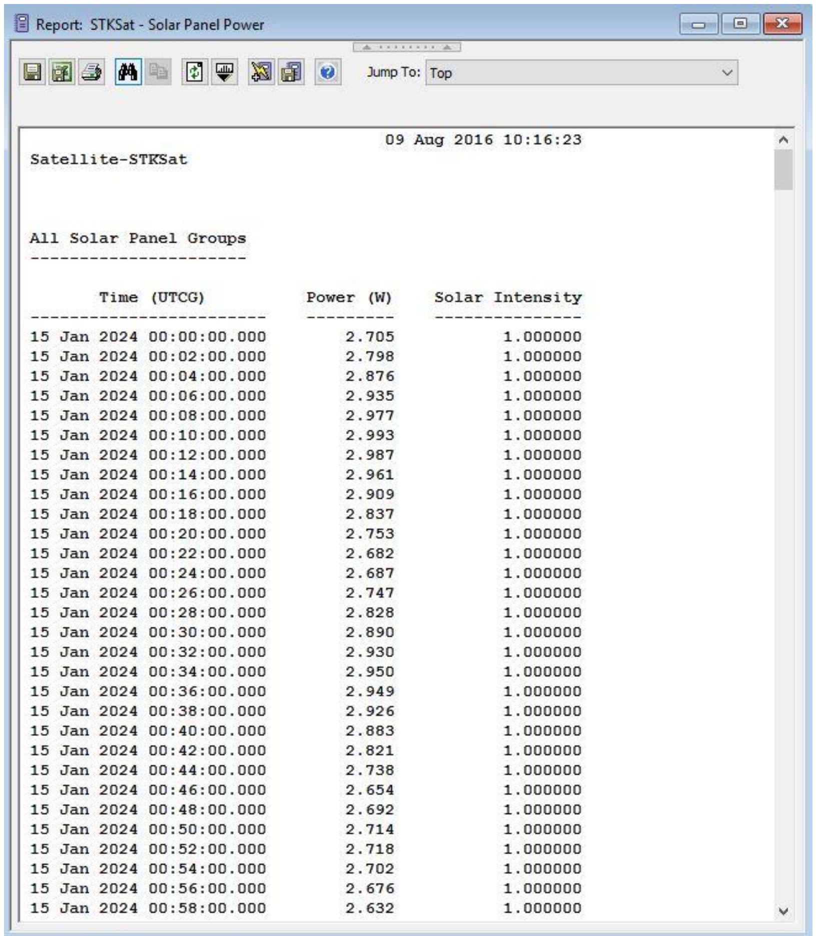
4. Click the OK button to dismiss the Properties window.
5. Rename the chain to “Observe”.

Section 2: Power Generation Analysis

Observing Solar Power Generation Over One Year

Due to Earth’s elliptical orbit around the Sun, the Earth does not consistently receive solar rays of the same strength from month to month or even day to day. The same applies to satellites. We will now explore how STKSat generates power over the course of one year by measuring power generation at the middle of each month and then comparing the results.

1. Right-click STKSat in the Object Browser, select Satellite, and then click on Solar Panel…
2. A white window will popup showing the CubeSat. This window is simply for visual of the CubeSat as the tool is run. In the other popup window, select all solar panel groups by holding down the Ctrl key and clicking each group so that they are all highlighted.
3. Make sure no objects are being used for obscuration by clicking the Deselect All button.
4. Set the Time Step to 120 seconds.
5. Change the Start time to 15 Jan 2024 00:00:00.000 UTCG and the stop time to 16 Jan 2024 00:00:00.000 UTCG.
6. Click the Compute button.
7. Click OK on any popup boxes that appear; the tool will then begin running.
8. Once the tool has collected all its data make sure the Type under Data Reporting is set to Power and that the Report option is selected. Click the Generate… button.
9. A report should be generated that looks similar to the one below:


Report: STKSat - Solar Panel Power

Jump To: Top

09 Aug 2016 10:16:23

Satellite-STKSat

All Solar Panel Groups

Time (UTCG)	Power (W)	Solar Intensity
15 Jan 2024 00:00:00.000	2.705	1.000000
15 Jan 2024 00:02:00.000	2.798	1.000000
15 Jan 2024 00:04:00.000	2.876	1.000000
15 Jan 2024 00:06:00.000	2.935	1.000000
15 Jan 2024 00:08:00.000	2.977	1.000000
15 Jan 2024 00:10:00.000	2.993	1.000000
15 Jan 2024 00:12:00.000	2.987	1.000000
15 Jan 2024 00:14:00.000	2.961	1.000000
15 Jan 2024 00:16:00.000	2.909	1.000000
15 Jan 2024 00:18:00.000	2.837	1.000000
15 Jan 2024 00:20:00.000	2.753	1.000000
15 Jan 2024 00:22:00.000	2.682	1.000000
15 Jan 2024 00:24:00.000	2.687	1.000000
15 Jan 2024 00:26:00.000	2.747	1.000000
15 Jan 2024 00:28:00.000	2.828	1.000000
15 Jan 2024 00:30:00.000	2.890	1.000000
15 Jan 2024 00:32:00.000	2.930	1.000000
15 Jan 2024 00:34:00.000	2.950	1.000000
15 Jan 2024 00:36:00.000	2.949	1.000000
15 Jan 2024 00:38:00.000	2.926	1.000000
15 Jan 2024 00:40:00.000	2.883	1.000000
15 Jan 2024 00:42:00.000	2.821	1.000000
15 Jan 2024 00:44:00.000	2.738	1.000000
15 Jan 2024 00:46:00.000	2.654	1.000000
15 Jan 2024 00:48:00.000	2.692	1.000000
15 Jan 2024 00:50:00.000	2.714	1.000000
15 Jan 2024 00:52:00.000	2.718	1.000000
15 Jan 2024 00:54:00.000	2.702	1.000000
15 Jan 2024 00:56:00.000	2.676	1.000000
15 Jan 2024 00:58:00.000	2.632	1.000000

Figure 9 - Solar Panel Power Report

   a. Scroll down to the last section of the report to make sure that it includes information for all solar panel groups.

10. In the Report window, click the button in the top left corner called Save as .csv. Navigate to a desired location, rename the File name to January, and click Save.
11. Open your "January" Excel file and delete rows 2-4327 and all of the data in them, then save your file. (Highlight rows – right click – "Delete…" – "Entire row".)
12. Repeat steps 5 through 11 for each of the remaining months in the year, changing the start and stop times to the 15th and 16th of the appropriate month. STK uses the first three letters of each month as its designation (September = Sep).

Comparing Solar Power Generation Over One Year

We will now sum up the data for each month within the Excel files and then create a separate file to summarize the results for comparison. An example spreadsheet can be found in the Supporting Materials folder of the downloaded .zip file.

1. Open up a new Excel spreadsheet and Save As "Solar Power Year Summary".
2. Create 3 columns with the following headings: Month, #, Power (W).

3. Type in each month and its corresponding number (1, 3, etc).
4. Open the January.csv excel file.
5. Click inside the E1 box and type =SUM(B:B). Hit Enter.
   a. Excel will sum the power generation data for each time step and report the total power generation.
6. Type the total power result into the Power (W) column of the summary spreadsheet. Copy and pasting the value may result in an error.
7. Repeat the above steps for each of the remaining months.
8. Highlight the # and Power (W) columns and generate a Scatter with Smooth Lines and Markers plot.
9. Format the chart as desired.
10. Observe how STKSat generates power over the course of one year.
    a. Note: A satellite's orbital parameters play a large role in how its solar power generation varies over the year. A satellite with different orbital parameters wouldn't necessarily show the same trend as STKSat.

       Deliverable 1: What month does STKSat generate the least amount of power? What month does STKSat generate the most amount of power?

Section 3: Gathering Power Consumption/Power Generation Data in STK

The most important requirement for solar and power design is to make sure that your satellite constantly has enough power to run all of its functions. We can reason that we want to design a power system that can sustain the satellite during the time when it is generating the least amount of power.

We will further analyze the month determined above and look for the longest access time between STKSat and Exton that is in either penumbra or umbra. We will assume here that STKSat's transmitter and receiver will be active during the entire time of access; thus STKSat will experience a lengthened period of power draw while operating during the month that it receives the least amount of power generation from sunlight. The power draw from the camera will also be accounted for but it is not the main focus since it draws much less power than the transmitter.

Determining Penumbra/Umbra Access Times and Maximum Access Duration

1. Since we are now only interested in the month that STKSat generates the least amount of power we will shorten our Scenario interval.
   a. Right-click the scenario Laboratory_2_Solar_and_Power_Design in the object browser and click Properties.
   b. Under Analysis Period, set the Start time to be the first of the month determined above with a time of 00:00:00.000 UTCG and set the Stop time to be the first of the following month with a time of 00:00:00.000 UTCG. Make sure the start year is 2024 and the stop year fits accordingly.

i. *Example*:
Month with least power generation = May
Start Time is 1 May 2024 00:00:00.000 UTCG
Stop Time is 1 Jun 2024 00:00:00.000 UTCG

2. We only want to report access times when our satellite is either in penumbra or umbra.
   a. Right-click STKSat in the object browser and click Properties.
   b. Click the Constraints -> Sun tab.
   c. Click the checkbox next to Lighting and change the type to "Penumbra or Umbra".
   d. Click OK.
3. Right-click STKSat in the object browser and click Access…
4. Double check that the top of the window says Access for: STKSat.
5. Select Exton from the list and click the Compute button near the top-left corner of the window.
6. On the right-side of the window under Reports click the Access… button.
7. Scroll down to the bottom of the report and look under Global Statistics. Note the start and stop times for the max duration of access.

Deliverable 2: What is the start and stop time (date included) for the longest access duration while STKSat is in penumbra/umbra?

Calculating Total Power Generation

Now that we know the start and stop time of STKSat's longest access duration while in penumbra or umbra, we will analyze a brief Scenario Interval around this access time.

1. We will again shorten our Analysis Period of our Scenario.
   a. Right-click the scenario Laboratory_2_Solar_and_Power_Design in the object browser and click Properties.
   b. Under Analysis Period, set the Start time to be 24 hours before the start time of the longest access duration and set the Stop time to be 24 hours after the stop time of the longest access duration.
      i. *Example:*

Table 10 – Detailed Scenario Interval

Time Component	Start Time	Stop Time
Longest Access Duration	7 May 2024 06:27:13.051	7 May 2024 06:38:52.000
Scenario Analysis Period	6 May 2024 06:27:13.051	8 May 2024 06:38:52.000

We will now use the Scenario Analysis Period defined above and calculate our total power generation over the time period by using the Solar Panel tool.

1. Right-click STKSat in the object browser, select Satellite, and then click Solar Panel…
2. Click the down arrow next to the Interval box and select "Use Scenario Interval".
3. Select all solar panel groups by holding down the ctrl key and clicking on them.
4. Make sure no objects are being used for obscuration by clicking the Deselect All button.
5. Change the Time Step to 60 seconds.
6. Click the Compute button.

7. Click OK on any popup boxes that appear; the tool will then begin running (should take about one minute).
8. Once the tool has collected all its data make sure the Type under Data Reporting is set to Power and that the Report option is selected. Click the Generate… button.
9. In the Report popup window click the Save as .csv button and save the report with the File name “Total Power Generation”.
10. Open your “Total Power Generation” Excel file and delete rows 2-17353 and all of the data in them, then save your file. (Highlight rows – right click – “Delete…” – “Entire row”.)
11.

Calculating Total Power Consumption

We will use the Analysis Workbench ( ) add-on laboratory to compute the total power consumption of STKSat over the detailed interval defined in the previous section.

Camera Consumption

Before calculating the camera consumption, we must determine the times when the camera is active and imaging volcanoes.

1. Right-click Observe in the object browser, select Chain, and then click Compute Accesses.
2. Right-click Observe in the object browser and click Report & Graph Manager.
3. Make sure Observe is highlighted in the left-side window.
4. In the right-side window double-click on Complete Chain Access to run the report. This report gives us the times that STKSat’s camera will be imaging the volcanoes within our defined Scenario Analysis Period. Close the report.

We will now use this chain access to calculate the cameras power consumption over the Scenario Interval.

5. On the main toolbar click Analysis and then click Analysis Workbench ( ).
6. Select the Calculation tab.
7. In the left-side window highlight STKSat.
8. In between the two windows there is a column of 4 buttons. Click the first one that says Create new Scalar Calculation ( ).
9. Change the Type to Constant.
10. Name the component Camera_Consumption.
11. Set the Constant Value field to -3.25 and leave the Dimension as Unitless.
    a. We will assume that our reaction wheels (3W power draw) are being used when STKSat is close enough to a volcano. This will allow STKSat to rotate in order to keep the camera pointed at the volcano.

We only want to calculate this power draw when the Camera is being used (when the Camera has access). We will set up another Scalar Calculation to do this.

12. Click the Create new Scalar Calculation button again.
13. Change the Type to Integral.
14. Name the component Camera_Consumption_Calc.
15. Set the Input Scalar to Camera_Consumption which will be listed under the My Components folder in the right-side window.
16. Change the Accumulation Type to Cumulative to Current.
17. Click the Advanced Options… button.
18. In the top-right of the window, click the ellipsis next to Time Limits.
    a. Select Chain_Link in the left-side window and select CompleteChainAccessIntervals in the right-side window. Click OK.
19. Click OK two more times to create the new Scalar Calculation.

Transmitter Consumption

1. Navigate to the Analysis Workbench window.
2. Select the Calculation tab.
3. In the left-side window highlight STKSat.
4. In between the two windows there is a column of 4 buttons. Click the first one that says Create new Scalar Calculation.
5. Change the Type to Constant.
6. Name the component Transmitter_Consumption.
7. Set the Constant Value to -6 and leave the Dimension Unitless.

We only want to calculate this power draw when STKSat has line of sight access to Exton. We will set up another Scalar Calculation to do this.

8. Click the Create new Scalar Calculation button again.
9. Change the Type to Integral.
10. Name the component Transmitter_Consumption_Calc.
11. Set the Input Scalar to Transmitter_Consumption which will be listed under the My Components folder in the right-side window.
12. Change the Accumulation Type to Cumulative to Current.
13. Click the Advanced Options… button.
14. In the top-right of the window, click the ellipsis next to Time Limits.
    a. Select Satellite-STKSat-To-Place-Exton in the left-side window and select AccessIntervals in the right-side window. Click OK.
15. Click OK two more times to create the new Scalar Calculation.

At this point we need to change STKSat's sun lighting properties back so that the access times are not restricted to only penumbra or umbra.

16. Right-click STKSat in the object browser and click Properties.
17. Go to the Constraints -> Sun tab.
18. Uncheck the box next to Lighting.
19. Click OK to dismiss the Properties window.

Combined Variable Consumption

We will now combine our camera consumption calculation and our transmitter consumption calculation together to give us the total variable consumption.

1. Navigate to the Analysis Workbench window.
2. Select the Calculation tab.
3. In the left-side window highlight STKSat.
4. In between the two windows there is a column of 4 buttons. Click the first one that says Create new Scalar Calculation.
5. Change the Type to Function(x,y).
6. Name the component Variable_Consumption_Function.
7. Leave the default Function (should be a*x+b*y).
8. Under Arguments, click the ellipsis next to x and set it to the Camera_Consumption_Calc scalar calculation listed under My Components. Click OK.
9. Under Arguments, click the ellipsis next to y and set it to the Transmitter_Consumption_Calc scalar calculation listed under My Components. Click OK.
10. Leave all other defaults and click OK.

Constants Consumption

STKSat is constantly using power for the spacecraft computer and the receiver. We will group the total constant value in a Scalar Calculation.

1. Navigate to the Analysis Workbench window.
2. Select the Calculation tab.
3. In the left-side window highlight STKSat.
4. In between the two windows there is a column of 4 buttons. Click the first one that says Create new Scalar Calculation.
5. Change the Type to Constant.
6. Name the component Constants_Consumption.
7. Set the Constant Value to -0.75 and leave the Dimension Unitless.
8. Click OK.

We want STK to match the time steps of this scalar calculation with our scenario interval.

9. Click the Create new Scalar Calculation button again.
10. Change the Type to Integral.
11. Name the component Constants_Consumption_Calc.
12. Set the Input Scalar to Constants_Consumption which will be listed under the My Components folder in the right-side window.
13. Change the Accumulation Type to Cumulative to Current.
14. Click the Advanced Options… button.
15. In the top-right of the window, click the ellipsis next to Time Limits.

b. Select the scenario Laboratory_2_Solar_and_Power_Design in the left-side window and select AnalysisInterval in the right-side window. Click OK.

16. Click OK two more times to create the new Scalar Calculation.

Total Power Consumption

Finally, we will now combine the variable consumption with the constant consumption to give us the total power consumption.

1. Navigate to the Analysis Workbench window.
2. Select the Calculation tab.
3. In the left-side window highlight STKSat.
4. In between the two windows there is a column of 4 buttons. Click the first one that says Create new Scalar Calculation.
5. Change the Type to Function(x,y).
6. Name the component Total_Consumption_Function.
7. Leave the default Function (should be a*x+b*y).
8. Under Arguments, click the ellipsis next to x and set it to the Variable_Consumption_Function scalar calculation listed under My Components. Click OK.
9. Under Arguments, click the ellipsis next to y and set it to the Constants_Consumption_Calc scalar calculation listed under My Components. Click OK.
10. Leave all other defaults and click OK.

We now want to run a report using the total power consumption Scalar Calculation and export it to Excel for further analysis.

1. Right-click the newly created Scalar Calculation titled Total_Consumption_Function and click Report/Graph…
2. Under Select Report Elements only highlight the 2nd element in the list.
3. Leave all other defaults and click Create Report.
4. Once the report is generated click in the top-left corner to Save as .csv. Name the File "Total Power Consumption" and click Save. You do not need to edit this file or delete any data points.

Section 4: Final Analysis to Determine Solar Panel/Battery Selection

We will now use a pre-created Excel spreadsheet to condense all of our information together and to run our final analysis.

1. Navigate to the .zip folder and open the Excel spreadsheet titled "Final Power Analysis".
2. In your own folder, open the file titled "Total Power Generation" that we created earlier. Copy the entire column of values from columns A and B (The Time and the Power) and paste them (Make sure you right-click and select the paste Values option to keep the cells colored) in cell B12 in the Final Power Analysis spreadsheet. This fills both columns B and C.

a. The default model file in STK uses solar panels with an efficiency of 0.28. Rather than modifying the model file and re-running the Solar Panel Tool, we simply adjust the already obtained data to reflect the other efficiencies. The Excel spreadsheet is already set up to do this.

3. In your own folder, open the file titled "Total Power Consumption" that we created earlier. Copy the entire column of values from column B and paste them in cell F12 in the Final Power Analysis spreadsheet.
4. All values in the spreadsheet should now automatically fill in. Observing the solar panel/battery combination costs, you want to select the cheapest one that satisfies the mission requirements.

Deliverables 3&4: Select which solar panel system and which battery you would like to use and write them in the Deliverables table at the beginning of the laboratory.

Laboratory 3: Communications Design

Laboratory Overview

This laboratory provides an end-to-end communications system design experience that follows the example *STKSat* mission from AGI's Educational Alliance Program – CubeSat Mission Design Series. The accompanying lesson for this laboratory can be found in the lessons folder of this series archive found here.

Objective

The objective of this laboratory is to:

- Model a complete RF link between the example mission ground station in Exton, PA and the *STKSat* spacecraft using STK.
- Perform trade studies on commercial off-the-shelf (COTS) CubeSat communications components to optimize the RF link.
- Establish a link and telemetry budget for the *STKSat* mission.
- Model environmental losses on the RF link using STK.

Requirements

Derived from mission requirement four established in Laboratory 0 – Series Overview, the following requirements describe the *STKSat* mission communications system:

6. *STKSat* shall downlink health and imagery data at an ultra-high frequency (UHF) of around 435 MHz.
7. *STKSat* shall receive uplink from the ground station at a very-high frequency (VHF) of around 145 MHz.
8. *STKSat* shall operate with a link margin greater than or equal to 3 dB for imagery and health data to be considered acceptable.
9. *STKSat* shall communicate with a bit error rate of less than or equal to 10^{-3} for imagery and health data to be considered acceptable.

Assumptions

The *STKSat* mission ground station in Exton, PA uses the following equipment:

- Hy-Gain UB-7030SAT Cross-Polarized Yagi-Uda UHF Antenna
- Hy-Gain 216SAT Cross-Polarized Yagi-Uda VHF Antenna
- iCOM 910H UHF/VHF Transceiver
- Yaesu G-5500 Rotor Controller (Satellite Tracking Capable)

The *STKSat* mission ground station in Exton, PA has the following receiver properties:

- 6.5 dB of Pre-Receive Losses
- 1 dB of Pre-Demodulation Losses
- 3 dB of line loss from the antenna to the low-noise amplifier (LNA)
- 2 dB of line loss from the LNA to the receiver
- An antenna to LNA transmission line temperature of 290 K

- An LNA noise figure of 2 dB
- An LNA temperature of 60 K.
- An LNA to receiver transmission line temperature of 130 K
- An LNA gain of 20 dB
- A receiver sensitivity of -156 dBW

The *STKSat* mission ground station in Exton, PA has the following transmitter properties:

- An antenna gain of 100 W (20 dBW)
- Available modulations: FSK, AFSK, MSK, GMSK

CubeSat COTS Transceivers

The following is a list of commercial off-the-shelf transceivers and some of their general specifications.

Table 11 - CubeSat COTS Transceivers

Component	Specifications
CPUT CubeSat Transceiver	Data Rate: 9600 bps (uplink and downlink) Transmitter Output Power: adjustable 27 – 33 dBm Transmit Power Draw: 4 – 10 W (27 – 33 dBm) Receiver Sensitivity: -120 dBm Receiver Power Draw: 250 mW Modulation: GMSK/MSK
AstroDev Helium He-100 CubeSat Transceiver	Data Rate: 9600 bps (uplink and downlink) Transmitter Output Power: 30 dBm Transmitter Power Draw: 6W Receiver Sensitivity: -104.7 dBm Receiver power Draw: 200 mW Modulation: GMSK/MSK
ISIS CubeSat Transceiver	Data Rate: 1200 bps (uplink and downlink) Transmitter Output Power: 28 dBm Transmitter Power Draw: 5 W Receiver Sensitivity: -104 dBm Receiver Power Draw: 200 mW Modulation: AFSK/FSK

The specifications of these transceivers will be used to perform quantitative trade studies on the communications capabilities of each of these components. Ultimately, the goal of this laboratory is to characterize a communications link between *STKSat* and the ground station in order to choose the spacecraft components that best satisfy the link requirements.

Deliverables

Place your answers for all of the laboratory deliverables in the Table 12 below, or on a separate sheet provided by your instructor. Remember to show your work in calculations for full credit.

Table 12 - Laboratory 3 Deliverables

Deliverable	Answer
Deliverable 1: *Link BER*	
Deliverable 2: *Calculate Rcvd. Frequency*	
Deliverable 3: *Calculate RIP*	
Deliverable 4: *Doppler Shift*	
Deliverable 5: *Prop. Loss*	
Deliverable 6: *Carrier Pwr. vs. RIP*	
Deliverable 7: *Link Margin*	
Deliverable 8: *Uplink vs. Downlink*	
Deliverable 9: *Modulation*	
Deliverable 10: *Access Time*	
Deliverable 11: *Component Parameter Testing*	
Deliverable 12: *Component Selection*	

Section 1: Setting Up the Scenario

In this section, you will setup the scenario that will be used throughout the rest of this laboratory. This involves adding the *STKSat* spacecraft with the orbit determined in Laboratory 1 – Orbit Design as well as the basic objects for representing a ground station facility.

Adding the *STKSat* Satellite

1. Open a new instance of STK ( ) and create a new Scenario ( ) with the following information:

Table 13 - Laboratory 3 Scenario Settings

Field	Value
Name	Laboratory_3_Communications_Design
Description	This is the scenario for Laboratory 3 – Communications Design of AGI's Educational Alliance Program CubeSat Mission Design Series.
Location	Leave Default
Start	1 Jan 2024 00:00:00.000 UTCG
Stop	2 Jan 2024 00:00:00.000 UTCG

2. From the Insert menu, select New ( ) to open the Insert STK Objects window.
3. Select the Satellite ( ) object type and select the Insert Default method. Then, click Insert.
4. Change the Satellite Name to STKSat then right click on STKSat and go to its Properties.
5. Change the following parameters.

Table 14 - Laboratory 3 STKSat Parameters

Parameter	Value
Semimajor Axis	6780 km
Eccentricity	0.00
Inclination	51.6 deg
Argument of Perigee	0 deg
RAAN	0 deg
True Anomaly	0 deg

1. Change the propagator to J2Perturbation.
2. Click the Apply button to apply the changes. Notice the propagated orbit is now visible in the 2D and 3D Graphics Windows. Keep the properties window open.
3. In the Properties window, on the 3D Graphics – Model page, change the Model File field to the file *cubesat_1u.dae*.
4. Click the Apply button to apply the changes. Click OK to close the window.

Adding a Ground Station Facility

6. In the Insert STK Objects window, select Facility ( ). Select the Insert Default method. Click the Insert button to insert the Facility.
7. Right-click on the Facility ( ) object in the Object Browser and rename it to "Exton".

Note that when inserting a default Facility, it is placed at the coordinates of AGI's headquarters in Exton, PA. The location of the ground facility will be placed in a nearby field with the following coordinates:

Latitude: 40.0388 deg
Longitude: -75.6005 deg

8. Right-click on the Facility () object in the Object Browser and click Properties ().
9. In the Properties window, browse to the Basic – Position page. Modify the Latitude and Longitude fields to match the coordinates above.
10. Click the Apply button to apply the changes. Then, click the OK button to close the properties window.
11. Right-click on Exton in the Object Browser and select Zoom To. Notice the location of the Facility in a nearby field.

Adding a Satellite Tracking Sensor

Typically, many ground stations have satellite tracking capabilities. A ground station's antennas are attached to an antenna rotor system that can be used to change the azimuth and elevation of the antennas thus allowing directional pointing and tracking.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Sensor ( ). Select the Insert Default method. Click the Insert button to insert the Sensor.
3. In the Select Object window, select the Exton facility and click OK. Notice the new sensor object is added under the Exton facility in the object browser.
4. Right-click on the Sensor ( ) object in the Object Browser and rename it "AntennaRotor".
5. Right-click on AntennaRotor and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change the Cone Half Angle to 2 deg. In this case, the cone half angle is only for aesthetic purposes to show pointing and tracking capabilities of the ground station.
7. Browse to the Basic – Pointing page and change the Pointing Type from Fixed to Targeted.
8. Move the STKSat object from the Available Targets section to the Assigned Targets section by selecting the object and clicking the right arrow button.
9. Click the Apply button to apply the changes and click OK to close the window.
10. Play through the scenario by using the Play ( ) button at the top of the screen. Watch as the AntennaRotor sensor tracks STKSat as it passes overhead.

Adding the Ground Station Yagi-Uda Antennas

Commonly, small organizations and universities will use low-cost Yagi-Uda antennas on their ground station in combination with amateur band radios to communicate with amateur satellites. Yagi-Uda antennas are directional and can be attached to rotors to enable tracking of satellites as they pass overhead.

Currently, STK does not include built-in antenna models for Yagi-Uda antennas. Therefore, an external antenna radiation pattern file generated in MATLAB will be imported into STK. For more information on the generation of custom antenna radiation patterns using MATLAB and the Antenna Toolbox, click the link.

Ensure you have downloaded or extracted the *uhf_yagi_pattern.txt* and *vhf_yagi_pattern.txt* files located in the Supporting Material folder for this laboratory. They will be used in this section.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Antenna ( ). Select the Insert Default method. Click the Insert button to insert the Antenna.
3. In the Select Object window, select AntennaRotor and click OK. Notice the new Antenna object is added under the AntennaRotor object in the object browser.
4. Right-click on the Antenna ( ) in the Object Browser and rename it "ExtonUHFAntenna".

5. Right-click on ExtonUHFAntenna and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to External Antenna Pattern.
7. Change the Design Frequency field to 435 MHz.
8. In the External Filename field, browse to the *uhf_yagi_pattern.txt* file and open it.
9. Click the Apply button to apply the changes. Then, click OK to close the window.
10. Repeat steps 1 through 9 to create another Antenna object, naming the Antenna object "ExtonVHFAntenna", using a Design Frequency of 145 MHz, and using the antenna pattern file *vhf_yagi_pattern.txt*.

Adding the Ground Station Transmitter

Modeling transmitters in STK involves configuring the output power of the system, the modulation technique being utilized, system losses, data rate, and properties of the antenna connected to the transmitter.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Transmitter ( ). Select the Insert Default method. Click the Insert button to insert the Transmitter.
3. In the Select Object window, select Exton and click OK. Notice the new Transmitter object is added under the Exton facility object in the object browser.
4. Right-click on the Transmitter ( ) object located in the Object Browser and rename it "ExtonVHFTransmitter".
5. Right-click on ExtonVHFTransmitter and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to Complex Transmitter Model.
7. In the Model Specs tab, change the Frequency to 145 MHz. Change the Power to 20 dBW (100 W). Change the Data Rate to 9600 b/sec.
8. In the Antenna tab, change the Reference Type to Link.
9. In the Model Specs tab, change the Antenna Name to link to the ExtonVHFAntenna object.
10. In the Polarization tab, enable the Use checkbox. Change the polarization to Right-hand Circular. Yagi-Uda antennas are typically either right-hand or left-hand circularly polarized.
11. In the Modulator tab, change the Name field to MSK.
12. In the Signal Bandwidth section, ensure the Auto Scale option is enabled. This automatically calculates the bandwidth of the signal based on the frequency, data rate, and modulation technique.
13. In the Additional Gains and Losses tab, add a new post-transmit loss by clicking the Add button to the right. Change the new Gain field to -7 dB. This represents a post-transmit loss due to cable lengths, antenna coupling, polarization, etc.
14. Click the Apply button to apply the changes. Click OK to close the window.

Adding the Ground Station Receiver

Modeling receivers in STK involves configuring the internal and external system losses, the system noise temperature, the demodulation technique to be used, and properties of the antenna connected to the transmitter.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Receiver ( ). Select the Insert Default method. Click the Insert button to insert the Receiver.
3. In the Select Object window, select Exton and click OK. Notice the new Receiver object is added under the Exton facility object in the object browser.
4. Right-click on the Receiver ( ) object located in the Object Browser and rename it "ExtonUHFReceiver".
5. Right-click on ExtonUHFReceiver and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to Complex Receiver Model.
7. In the Model Specs tab, disable the Auto Track option and change the Frequency to 435 MHz. Change the Antenna to LNA Line Loss to 3 dB. Change the LNA gain to 20 dB. Change the LNA to Receiver Line Loss to 2 dB.
8. In the Antenna tab, change the Reference Type to Link.
9. In the Model Specs tab, change the Antenna Name to link to the ExtonUHFAntenna object.
10. In the Polarization tab, enable the Use checkbox. Change the polarization to Right-hand Circular. Yagi-Uda antennas are typically either right-hand or left-hand circularly polarized.
11. In the System Noise Temperature tab, select the Compute option. Change the Antenna to LNA Transmission Line Temperature to 290 K. Change the LNA Noise Figure to 2 dB and the Temperature to 60 K. Change the LNA to Receiver Transmission Line Temperature to 130 K.
12. In the Antenna Noise section, select the Constant option and change the value to 1200 K.
13. In the Demodulator tab, disable the Auto-select Demodulator option. Change the Name field to MSK.
14. In the Filter tab, ensure the Auto Scale option is enabled in the Receiver Bandwidth section.
15. In the Additional Gains and Losses tab, add a new Pre-Receive Loss by clicking the Add button on the right. Change the Gain value of the new loss to -7 dB. This represents a pre-receive loss due to antenna coupling, polarization, etc.
16. Add a new Pre-Demodulation Loss by clicking the Add button on the right. Change the Gain value for the new loss to -5 dB. This represents losses inside the receiver system between the antenna and the demodulator.
17. Click the Apply button to apply the changes. Click the OK button to close the window.

The ground station has now been configured with the hardware and assumptions described previously. Later, the ExtonUHFReceiver and ExtonVHFTransmitter objects will be used to model an RF link to the *STKSat* spacecraft.

Adding the Spacecraft Dipole Antennas

Dipole antennas are commonly used on small satellites due to their simple design, ease of deployment, and small stowage size. Dipole antennas are commonly spooled up inside a small part of the CubeSat and deployed using electrical burn wires or tape that dissolves in UV light.

STK includes a built-in model for dipole antennas. This model allows users to modify the design frequency, length, length-to-wave ratio, and efficiency. *STKSat* will utilize a separate dipole antenna for UHF and VHF communications. Due to the wavelength of these different amateur bands, the two dipole antennas will be two different sizes.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Antenna ( ). Select the Insert Default method. Click the Insert button to insert the Antenna.
3. In the Select Object window, select STKSat and click OK. Notice the new Antenna object is added under the STKSat object in the object browser.
4. Right-click on the new Antenna ( ) object in the Object Browser and rename it "STKSatUHFAntenna".
5. Right-click on STKSatUHFAntenna and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to Dipole.
7. Change the Design Frequency field to 435 MHz
8. Change the Length/Wave Length Ratio to 0.25. This configures the dipole as a half-wave dipole. The Length of the Dipole should automatically be updated when this value is changed.
9. Change the Efficiency to 50%. An Efficiency of 100% is unrealistic as no antenna is perfect. Typically, this value falls between the 70-80% range. Due to the amateur design of CubeSats, a value of 50% is used.
10. On the Basic – Orientation page, change the Azimuth value to 90 deg and the Elevation value to 90 deg. This will orient the dipole vertically with the spacecraft.
11. Click the Apply button to apply the changes. Then, click OK to close the window.
12. Repeat steps 1 through 10 to create another Antenna object, naming the Antenna object "STKSatVHFAntenna", using a Design Frequency of 145 MHz and the same values for Length/Wave Length Ratio and Efficiency. For orientation values, use an Azimuth value of 90 deg and an Elevation value of 0 deg.

Adding the Spacecraft Transmitter

Modeling transmitters in STK involves configuring the output power of the system, the modulation technique being utilized, system losses, data rate, and properties of the antenna connected to the transmitter.

The baseline transmitter that will be modeled is the CPUT VUTRX. The specs are as follows:

- Transmitter Output Power: adjustable 27 – 33 dBm
- Transmit Power Draw: 4 – 10 W (27 – 33 dBm)
- Data Rate: 9600 baud (same as b/sec)
- Modulation: GMSK/MSK

These values will be used to configure the transmitter object in STK.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Transmitter ( ). Select the Insert Default method. Click the Insert button to insert the Transmitter.
3. In the Select Object window, select STKSat and click OK. Notice the new Transmitter object is added under the STKSat satellite object in the object browser.
4. Right-click on the Transmitter ( ) object located in the Object Browser and rename it "STKSatUHFTransmitter".
5. Right-click on STKSatUHFTransmitter and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to Complex Transmitter Model.
7. In the Model Specs tab, change the Frequency to 435 MHz. Change the Power to 33 dBm. This is the maximum output power of the transmitter. Change the Data Rate to 9600 b/sec.
8. In the Antenna tab, change the Reference Type to Link.
9. In the Model Specs tab, change the Antenna Name to link to the STKSatUHFAntenna object.
10. In the Polarization tab, enable the Use checkbox. Change the polarization to Right-hand Circular.
11. In the Modulator tab, change the Name field to MSK.
12. In the Signal Bandwidth section, ensure the Auto Scale option is enabled. This automatically calculates the bandwidth of the signal based on the frequency, data rate, and modulation technique.
13. In the Additional Gains and Losses tab, add a new post-transmit loss by clicking the Add button to the right. Change the new Gain field to -7 dB. This represents a post-transmit loss due to cable lengths, antenna coupling, polarization, etc.
14. Click the Apply button to apply the changes. Click OK to close the window.

Adding the Spacecraft Receiver

Modeling receivers in STK involves configuring the internal and external system losses, the system noise temperature, the demodulation technique to be used, and properties of the antenna connected to the transmitter.

The baseline receiver that will be modeled is the CPUT VUTRX. The specs are as follows:

- Receiver Sensitivity: -120 dBm
- Receiver Power Draw: 250 mW
- Data Rate: 9600 baud
- Modulation: GMSK/MSK

These values will be used to configure the receiver object in STK.

1. From the Insert menu, select New ( ) to open the Insert STK Objects window.
2. In the Insert STK Objects Window, select Receiver ( ). Select the Insert Default method. Click the Insert button to insert the Receiver.
3. In the Select Object window, select STKSat and click OK. Notice the new Receiver object is added under the STKSat satellite object in the object browser.
4. Right-click on the Antenna ( ) object located in the Object Browser and rename it "STKSatVHFReceiver".
5. Right-click on STKSatVHFReceiver and click Properties ( ).
6. In the Properties window, browse to the Basic – Definition page and change Type to Complex Receiver Model.
7. In the Model Specs tab, disable the Auto Track option and change the Frequency to 145 MHz.
8. In the Antenna tab, change the Reference Type to Link.
9. In the Model Specs tab, change the Antenna Name to link to the STKSatVHFAntenna object.
10. In the Polarization tab, enable the Use checkbox. Change the polarization to Right-hand Circular.
11. In the System Noise Temperature tab, select the Compute option. Change the Antenna to LNA Transmission Line Temperature to 290 K. Change the LNA Noise Figure to 1 dB and the Temperature to 1000 K. Change the LNA to Receiver Transmission Line Temperature to 290 K.
12. In the Antenna Noise section, select the Constant option and change the value to 1200 K.
13. In the Demodulator tab, disable the Auto-select Demodulator option. Change the Name field to MSK.
14. In the Filter tab, ensure the Auto Scale option is enabled in the Receiver Bandwidth section.
15. In the Additional Gains and Losses tab, add a new Pre-Receive Loss by clicking the Add button on the right. Change the Gain value of the new loss to -20 dB. This represents a pre-receive loss due to antenna coupling, polarization, etc. This loss is greater for CubeSats due to the antenna design and lack of pointing capability.
16. Add a new Pre-Demodulation Loss by clicking the Add button on the right. Change the Gain value for the new loss to -12 dB. This represents losses inside the receiver system between the antenna and the demodulator. This loss is also greater for CubeSats due to size and technology constraints.
17. Click the Apply button to apply the changes. Click the OK button to close the window.

Section 4: Analyzing the RF Link

Computing Access Between the Transmitters and Receivers

Before an RF link can be analyzed in STK, access must be computed between the two endpoints of the link. In this case, access between the VHF transmitter on the ground station and the VHF receiver on the spacecraft as well as access between the UHF transmitter on the spacecraft and the UHF receiver on the ground station.

1. Right-click on the ExtonVHFTransmitter in the object browser and select Access ( ).
2. Expand the STKSat object and select STKSatVHFReceiver. Click the Compute button to compute access. The STKSatVHFReceiver object should become bolded.
3. Click the Select Object button at the top of the window to select a new object to compute access for. In the Select Object window, click STKSatUHFTransmitter.
4. Expand the Exton object and select ExtonUHFReceiver. Click the Compute button to compute access. The ExtonUHFReceiver object should become bolded.
5. Click the Close button to close the Access window.

Generating a Link Budget for Uplink

Now that access has been computer between the VHF transmitter on the ground station and the VHF receiver on the spacecraft, a link budget can be generated to describe this link.

1. Right-click on the ExtonVHFTransmitter object in the object browser and select Report & Graph Manager ( ).
2. In the Report & Graph Manager window, change the Object Type to Access.
3. Select the Facility-Exton-Transmitter-ExtonVHFTransmitter-To-Satellite… access object.
4. In the Styles section, browse through the Installed Styles section and select the Link Budget – Detailed report style. Click the Generate button.
5. Scroll to the right of the report. Note the values of C/N, Eb/No, BER, etc. Notice that the bit error rate (BER) values are roughly around the range of 10^{-4}.

    Deliverable 1: Scroll down through the report. What is the *smallest* bit error rate (BER) shown in the report?

    There are some very small bit error rates in the report. These outliers are somewhat unrealistic but indicate that the RF link between the ground station transmitter and the receiver on the spacecraft is strong at that point in time.

    These extremely small values indicate that there may be some loss not being accounted for. However, this is acceptable as the report on this RF link gives us a comprehensive overview of the link as a whole and we don’t really need a very high level of accuracy with CubeSats.

6. Scroll back through the report and find the columns titles Freq. Doppler Shift (kHz) and Rcvd. Frequency (GHz). Change the units of the Rcvd. Frequency (GHz) column to MHz by right-clicking on the title, selecting Rcvd. Frequency, and clicking Units.

7. Disable the Use Defaults option and select Megahertz (MHz) in the New Unit Value section. Click OK to close the window. The column units should now be in MHz.
8. Scroll down through the report and notice how the Rcvd. Frequency value shifts over time. This shift is called Doppler Shift. The Doppler Shift is the difference between the design frequency and the received frequency.

   > **Deliverable 2:** Using the design frequency of 145 MHz and a Doppler shift value of -1.363454 kHz, calculate the received frequency. Does the result match the Rcvd. Frequency value at 1 Jan 2024 05:04:22.000? What is the percent difference between the design frequency and the received frequency at this time?

9. Finally, scroll through the report and find the EIRP (dBW) and Prop Loss (dB) columns. Recall that the EIRP is the effective isotopic radiated power and that Prop Loss is signal loss as it travels from the transmitter to the receiver.

   In this case, the Prop Loss should be equal to the Free Space Loss as other environmental losses have not been modeled yet. The received isotropic power (RIP) is the difference between the EIRP and the propagation loss. The RIP is the received power at the receiver's antenna.

   > **Deliverable 3:** Using the transmitter EIRP value of 25.915 dBW and Prop Loss value of 139.3583 dB calculate the RIP. Does the result match the Rcvd. Iso. Power value at 1 Jan 2024 01:45:02.000 in the report? Using the report values, what is the percent difference between the EIRP and the RIP at this time?

   In STK the RIP includes both the effect of propagation loss and the effect of bandwidth overlap. This overlap is caused by a mismatch between the transmitted signal's bandwidth and the receiver bandwidth. This is another column shown in the link budget report style. This overlap may cause additional loss in calculations and thus a slightly weaker RIP.

Generating a Link Budget for Downlink

Now that access has been computed between the UHF transmitter on the spacecraft and the UHF receiver on the ground station, a link budget can be generated to describe this link.

1. Right-click on the STKSatUHFTransmitter object in the object browser and select Report & Graph Manager ( ).
2. In the Report & Graph Manager window, change the Object Type to Access.
3. Select the Satellite-STKSat-Transmitter-STKSatUHFTransmitter-To… access object.
4. In the Styles section, browse through the Installed Styles section and select the Link Budget – Detailed report style. Click the Generate button.
5. Scroll through the report and note the values of C/N, Eb/No, BER, etc. Notice that the bit error rate (BER) values are roughly around the range of 10^{-3}.

   The bit error rates of the UHF link are larger because the transmitter is now on the spacecraft. These transmitters output much less power than ground station transmitters.

6. Scroll through the report and compare the link values from the UHF link to the VHF link analyzed previously. Note changes in Freq. Doppler Shift, Rcvd. Iso. Power, C/N, Eb/No, BER, etc.

    Deliverable 4: How does the Freq. Doppler Shift of the UHF link compare to the Freq. Doppler Shift of the VHF link? What is the reason for the difference?

    Keep in mind that the UHF band is at higher frequencies than the VHF band.

Modeling Environmental Losses

An important aspect to modeling any RF link is modeling its losses. In STK, there are several built-in environmental models that allow modeling of losses due to rain, clouds and fog, atmospheric absorption, urban propagation, etc. For CubeSats, rain, cloud, and atmospheric absorption models are the most applicable.

Some of the models used in STK are based on recommendations from the International Telecommunication Union (ITU). These recommendations overview the valid ranges and base equations of these models.

1. Right-click on the Laboratory_3_Communications_Design scenario ( ) in the object browser and select Properties ( ).
2. In the Properties window, browse to the RF – Environment page. On the Environmental Data tab, enable the Use ITU-R P.618 Section 2.5 option. This option allows the use of some other ITU models and calculates the total propagation loss in accordance with the ITU recommendation.
3. In the Rain & Cloud & Fog tab, enable the Use option in the Rain Model section. Ensure that the ITU-R P618-10 model is selected (You can find this model under the “Previous Versions” folder).
4. Enable the Use option in the Clouds and Fog Model section.
5. In the Atmospheric Absorption tab, enable the Use option. Ensure the ITU-R P676-9 model is selected.
6. Click the Apply button to apply the changes. Click OK to close the window.
7. Return to the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… Link Budget – Detailed report window. Click the Refresh ( ) button at the top of the window to refresh the report data.

    Notice the changes in C/N, Eb/No, and BER. Scroll through the report and find the Atmos Loss (dB), Rain Loss (dB), and CloudsFog Loss (dB). Notice how these columns are now populated with dynamic data that changes over time.

    Deliverable 5: In the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… Link Budget – Detailed report, what is the *largest* Atmos Loss value? Using the Rain Loss and CloudsFog Loss values and the Atmos Loss value at this time, what is the total loss due to the modeled environment?

Calculating Link Margins and Generating Custom Reports

Link margins are used to describe the strength of a signal. Typically, a threshold value for some link parameter such as EIRP, Eb/No, received power, etc. is set. Then, value of that link parameter at a point in time is compared to the threshold. The difference between the actual link value and the threshold is the link margin.

Usually, the link margin threshold is set to a minimum value where the link closes. For example, receiver sensitivity defines the minimum signal strength a receiver can handle to maintain an RF link. When creating a link margin, the receiver sensitivity would be the link margin threshold. Then, the link margin value would tell you how close you are to that minimum strength.

In STK, this can be done with communication constraints and custom link reports.

1. Right-click on the ExtonUHFReceiver in the object browser and select Properties ().
2. On the Basic – Definition page in the Model Specs tab, check the Enable option in the Link Margin section. Change the Type field to Rcvd Carrier Power. Change the Threshold field to -156 dBW. This is the sensitivity of the receiver on the ground station.
3. Click the Apply button to apply the changes.
4. Open the Report & Graph Manager () window and ensure the Object Type is set to Access. Select the Satellite-STKSat-Transmitter-STKSatUHFTransmitter-To… access object.
5. Select the Laboratory_3_Communications_Design_Styles folder and click the Create new report style () button. Name the new report style Custom Link Budget.
6. In the resulting Properties window, enter Link Information into the filter field. Then, click the Filter button to filter the results.
7. Expand the Link Information data provider and add the Time, EIRP, Prop Loss, Rcvd. Iso. Power, Carrier Power at Rcvr Input, Rcvr Gain, BER, and Link Margin parameters by selecting them and clicking the right arrow button.
8. Select the Link Information-BER parameter in the Report Contents section. Click the Options button.
9. In the Options window, change the Notation field to Scientific (e). Click OK to apply the changes and close the window.
10. Click the Apply button to apply the changes. Click OK to close the Properties window.
11. Select the new Custom Link Budget report style and click the Generate button. Notice the format of the custom report and the new columns Carrier Power at Rcvr Input (dBW) and Link Margin (dB).

    The Carrier Power at Rcvr Input (dBW) column takes into account the EIRP, Prop Loss, Rcvr Gain, and Post-Transmit/Pre-Receive losses of the transmitter and receiver. Compare the Rcvd. Iso. Power and Carrier Power at Rcvr Input columns.

    > **Deliverable 6:** How does the Rcvd. Iso. Power compare to the Carrier Power at Rcvr Input? What is the reason for the difference?

12. Right-click on the STKSatVHFReceiver in the object browser and select Properties (![]).
13. On the Basic – Definition page in the Model Specs tab, check the Enable option in the Link Margin section. Change the Type field to Rcvd Carrier Power. Change the Threshold field to -120 dBm. This is the sensitivity of the CPUT VUTRX receiver on the spacecraft.
14. Click the Apply button to apply the changes.
15. Return to the Report & Graph Manager ( ) window and select the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… access object. Select the new Custom Link Budget report style and click the Generate button. Note the Carrier Power at Rcvr Input and Link Margin values for this uplink RF link.

Adding Communications Constraints

In STK, constraints can be used to limit access calculations. For example, by default, there is a line-of-site (LOS) constraint on all objects. Therefore, access is only computed when there is line of site between objects. There are also communications constraints that can be used to limit access to "acceptable" RF conditions.

From the communications mission requirements described in the overview of this laboratory, a link margin of at least 3 dB and a BER of at least 10^{-3} must be maintained for the link to be considered valid. These values can be used to constrain the data set to only show accesses that satisfy these requirements.

1. Open the ExtonUHFReceiver Properties window and browse to the Constraints – Comm page.
2. Enable the Min constraint for Power at Receiver Input and change the value to -156 dBW. This sets the minimum received power equal to the ground station receiver sensitivity.
3. Enable the Max constraint for Bit Error Rate and change the value to 1e-3. Note that the Max constraint is used because a smaller BER is better.
4. Enable the Min constraint for Link Margin and change the value to 3 dB.
5. Click the Apply button to apply the changes.
6. Re-open the Satellite-STKSat-Transmitter-STKSatUHFTransmitter-To… Custom Link Budget report. Click the Refresh ( ) button to refresh the data. Notice that the number of accesses and data points has decreased. Also, notice that all of the BER values are less than 10^{-3} and the Link Margin values are all greater than 3 dB.

Deliverable 7: What is the *smallest* link margin the newly-constrained report?

7. Open the STKSatVHFReceiver Properties window and browse to the Constraints – Comm page.
8. Enable the Min constraint for Power at Receiver Input and change the value to -120 dBm. This sets the minimum received power equal to the spacecraft receiver sensitivity.
9. Enable the Max constraint for Bit Error Rate and change the value to 1e-3. Note that the Max constraint is used because a smaller BER is better.
10. Enable the Min constraint for Link Margin and change the value to 3 dB.
11. Click the Apply button to apply the changes.

12. Re-open the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… Custom Link Budget report. Click the Refresh () button to refresh the data. Notice that the number of accesses and data points has decreased. Also, notice that all of the BER values are less than 10^{-3} and the Link Margin values are all greater than 3 dB.

    Deliverable 8: How do the link margins for the uplink compare to the link margins for the downlink (i.e. shorter, longer, fragmented, etc.)? What is the reason for this difference?

Section 5: Optimizing the Link

With uplink and downlink RF links established between the ground station and *STKSat* spacecraft, the various link parameters can be modified to optimize the link. These parameters include modulation technique, data rate, receiver sensitivity, and transmitter output power.

Modifying the Modulation Technique

In order to modify the modulation technique, the modulation settings for both the transmitter and receiver in a link must be modified.

1. Open the Properties () for the ExtonVHFTransmitter object and browse to the Basic – Definition page.
2. On the Modulator tab, change the modulator Name field from MSK to FSK.
3. Click the Apply button to apply the changes. Click OK to close the window.
4. Return to the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… report and refresh the data using the Refresh () button. Notice how the report now has no data available. This is because the VHF receiver on the spacecraft is still configured for MSK modulation.
5. Open the Properties () for the STKSatVHFReceiver object and browse to the Basic – Definition page.
6. On the Demodulator tab, change the demodulator Name field from MSK to FSK.
7. Click the Apply button to apply the changes. Click OK to close the window.
8. Return to the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… report and refresh the data using the Refresh () button. Notice the changes in BER and Link Margin.

   The Link Margin appears to be more evenly distributed across the data. This is due to the fact that the power spectral density (PSD) of FSK modulation is wider than that of MSK modulation.

9. Repeat steps 1 – 8 for the downlink RF link (i.e. modify the STKSatUHFTransmitter and ExtonUHFReceiver objects).

   > **Deliverable 9:** How does the downlink Custom Link Budget report when using MSK modulation compare to the downlink report when using FSK modulation?

Modifying the Data Rate

Unlike the process of changing the modulation technique, the data rate options only need to be changes on transmitters in the RF link.

1. Open the Properties () for the STKSatUHFTransmitter object and browse to the Basic – Definition page.
2. In the Model Specs tab, change the Data Rate from 9600 b/sec to 1200 b/sec.
3. Click the Apply button to apply the changes. Click OK to close the window.
4. Return to the Satellite-STKSat-Transmitter-STKSatUHFTransmitter-To… Custom Link Budget report and refresh the data using the Refresh () button.

Note the changes in BER and Link Margin. A lower data rate corresponds to a lower (better) bit error rate. However, the Link Margin values have also decreased. This illustrates the tradeoff between signal bandwidth and power.

5. Repeat steps 1 – 4 for the uplink RF link (i.e. modify the ExtonVHFTransmitter object).

Deliverable 10: Does the total access time for the downlink RF link increase or decrease as the data rate is decreased?

Modifying the Receiver Sensitivity

The receiver sensitivity only needs to be changed for the receiver in an RF link. Because the ground station configuration is already established, only the receiver sensitivity on the *STKSat* spacecraft will be modified.

1. Open the Properties () for the STKSatVHFReceiver object and browse to the Basic – Definition page.
2. In the Model Specs page, change the Link Margin Threshold value from -120 dBm to -105 dBm.
3. Browse to the Constraints – Comm page and change the Min constraint for the Power at Receiver Input from -120 dBm to -105 dBm.
4. Click the Apply button to apply the changes. Click OK to close the window.
5. Return to the Facility-Exton-Transmitter-ExtonVHFTransmitter-To… Custom Link Budget report and refresh the data using the Refresh () button.

   Note the decreased access times and smaller Link Margin values due to the less-negative sensitivity value. The more-negative the sensitivity, the stronger the link.

Modifying the Transmitter Output Power

Similar to changing the data rate, the output power only needs to be changed for the transmitter in an RF link. Because ground stations typically just transmit at their maximum output power, only the output power for the transmitter on *STKSat* will be modified.

1. Open the Properties () for the STKSatUHFTransmitter object and browse to the Basic – Definition page.
2. In the Model Specs page, change the Power value from 33 dBm to 31 dBm.
3. Click the Apply button to apply the changes. Click the OK button to close the window.
4. Return to the Satellite-STKSat-Transmitter-STKSatUHFTransmitter-To… Custom Link Budget report and refresh the data using the Refresh () button.

   Notice the link access times decrease due to the decreased transmit power. Also notice that the Link margin values decrease to very near the threshold value of 3 dB.

Section 6: Component Selection

This section is a culmination of all of the concepts introduced in the previous sections of this laboratory. In this section, you will modify the existing RF links modeled in STK to use the values for the two other CubeSat radios described in the overview (i.e. the ISIS and AstroDev radios). Then, based on the results, you will select the CubeSat radio that best suits the mission.

Deliverable 11: Modify the existing RF links in STK to use the values of (i) the existing CPUT CubeSat transceiver (ii) the AstroDev Helium 100 CubeSat transceiver and (iii) the ISIS CubeSat transceiver specified at the beginning of the lab. For each radio, provide the time duration, the highest BER, and the highest link margin of the first uplink and downlink interval. Leave the previous established constraints and atmospheric effects and use 5 seconds step size for the RF reports.

Deliverable 11 Hints:

- Use the techniques introduced in Section 5 to modify the various transmitter and receiver settings.
- Use the Custom Link Budget report created in Section 4 to generate the BER and Link Margin data.
- The ground transmitter will remain constant except the data rate and modulation type (MSK or FSK).
- The ground receiver will remain constant except for the modulation type.

Deliverable 12: Based off the results from deliverable 11 which CubeSat radio best satisfies the mission requirements and provides the most communication time? Does this communication time come at a cost, such as an increase in power draw? If you have completed Laboratory 2, could this effect your battery and solar panel selection?