Simulation-To-Flight 1 (STF-1): Automating the Planning, Scheduling, Assessment and Data Processing/Reduction for a Small Satellite

Mark Suder, Justin Morris, Scott Zemerick, Matt Grubb
NASA's Independent Verification and Validation Program
Suite 2200, 5000 NASA Blvd., Fairmont, WV 26554; 681-753-5250
mark.suder@tmctechnologies.com

John Lucas
NASA Goddard Space Flight Center
B11, S232F, 8800 Green Belt Rd., Greenbelt, MD 20770; 301-286-0581
John.P.Lucas@nasa.gov

ABSTRACT

On December 16, 2019, a 3-U CubeSat named STF-1 launched as West Virginia's first spacecraft. This event marked the culmination of a run-up to launch involving the production of the spacecraft, creation/configuration of command and control infrastructure, and the evolution of its co-creation, the NASA Operational Simulator for Small Satellites (NOS[3]). This event also marked the beginning of a new phase: operations. While plans, procedures, and infrastructure were already in place or started for operations, many lessons were learned during the operations phase, especially during early operations (first month/commissioning phase). Additional plans, procedures, and infrastructure, especially related to communication planning and automated data processing, were created and developed to fill needs for the operation of the STF-1 mission.

This paper and presentation will overview the STF-1 operations team's solutions to addressing the many needs of operating a low-earth orbiting CubeSat mission with a single ground antenna that is shared and scheduled with several other missions. The STF-1 operations team deployed a combination of virtualization technologies, ground station technology solutions, collaboration software, custom planning software solutions, and existing ground antenna scheduling solutions to create an effective and efficient CubeSat operations environment. The end-solution satisfied the operations stakeholders, which include NASA, its industry partner TMC Technologies, and four independent professor-student teams at West Virginia University.

INTRODUCTION

Simulation-to-Flight 1 (STF-1)[1] is a 3-unit CubeSat and is West Virginia's first spacecraft. STF-1 launched on December 16, 2019, on a Rocket Lab Electron rocket from Mahia, New Zealand, as part of NASA's Educational Launch of Nanosatellites (ELaNa) XIX mission.

STF-1 has six main objectives:

1. Demonstrate development lifecycle value of a software only SmallSat simulator – the achievement of this goal has been discussed in several previous publications[2,3,4]

2. Demonstrate a cluster of redundant Micro-Electro-Mechanical Systems (MEMS) Inertial Measurement Units (IMUs) to overcome size, weight, and power constraints normally associated with IMUs

3. Develop and assess estimate strategies to maximize precise orbit determination accuracy from duty-cycled Global Positioning System (GPS) receiver operations

4. Measure the local plasma environment and energetic particles (SPW or space weather)

5. Assess III-V Nitride-Based materials and shielding required for use in optoelectronic sensors that can be used for short-range distance measurement and shape rendering (CSEE or computer science and electrical engineering)

6. Provide statewide educational outreach

Figure 1 below highlights the key subsystems and experimental payloads on STF-1 and additional information about the STF-1 mission can be found at http://www.stf1.com .

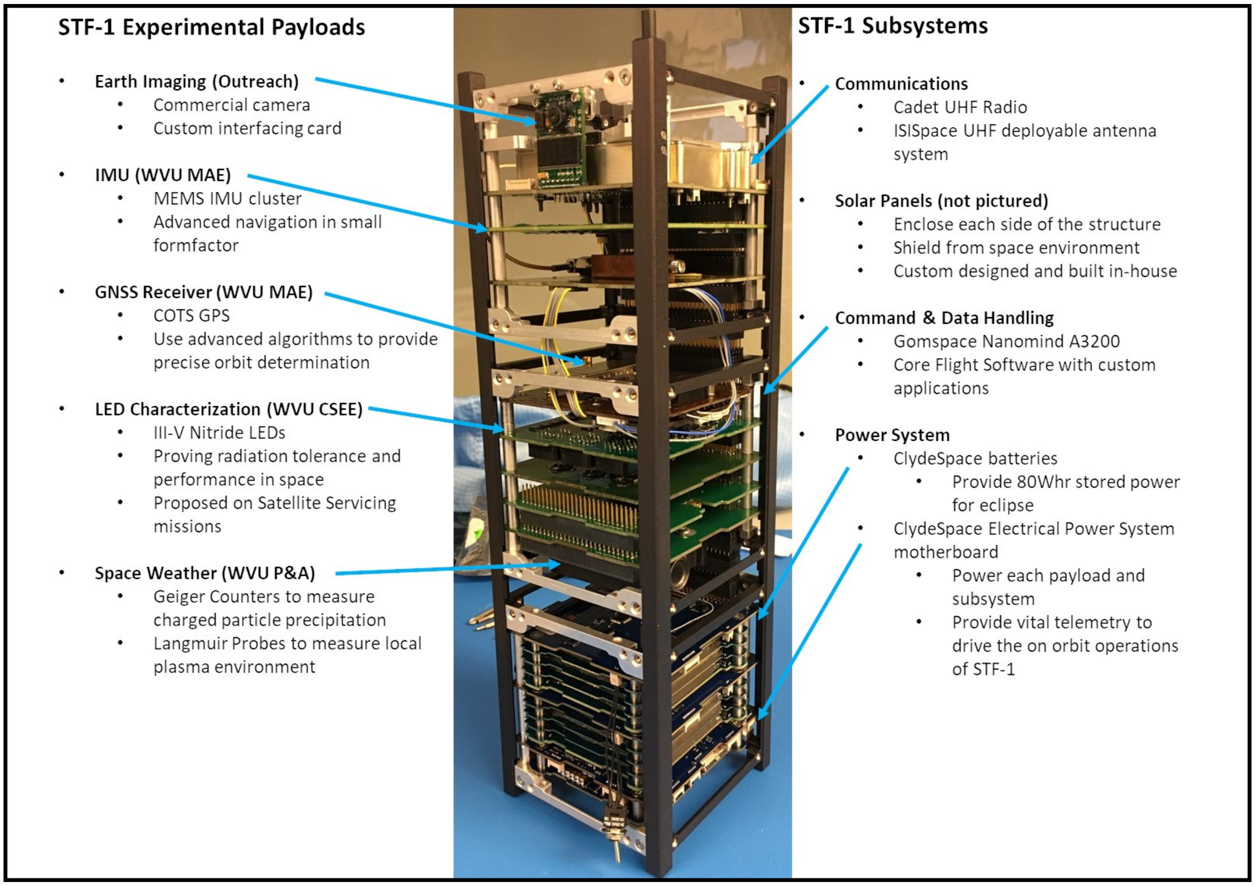


Figure 1: STF-1 Payloads and Subsystems

STF-1 was launched into an orbit with an altitude of approximately 500 km and an inclination of 85 degrees. STF-1 has an Ultra High Frequency (UHF) radio and utilizes an antenna at the NASA Wallops Flight Facility (WFF) in Virginia. Based on these mission parameters, STF-1 is in view of WFF approximately 4 to 6 times per day for approximately 10 minutes. It should be noted that the antenna at WFF supports a number of small satellite missions and is primarily a weekday operation, so STF-1 is not allocated contact time every time it is in view of WFF. In addition, STF-1 has no active attitude control, so it is freely tumbling in space.

Another item of note is that the ELaNa XIX mission launched 10 different CubeSat missions and resulted in 14 different objects being tracked and reported as two-line element (TLE) sets by the U.S. Strategic Command (USSTRATCOM). STF-1 depends on using the two-line element sets for the WFF antenna for tracking. Since the TLEs are based upon non-cooperative tracking data, USSTRATCOM relies on satellite operators to identify which numbered object is their satellite. As a result, the process of identifying which numbered object was STF-1 required educated guesswork and attempts to point the WFF antenna at various numbered objects. To support this effort, STK software from AGI was used to generate scenarios in order to provide a conceptual view of what a contact might look like. Figure 2 below shows an image from the STK scenario from when the first contact was made with STF-1 on December 19, 2019. In this image, STF-1 (STF-1_43852) is shown in green passing overhead of the United States. The view is looking over the Great Lakes and generally to the east. Also shown is the WFF antenna location (WFF) in blue, and a blue line indicating line of sight between the antenna and STF-1. Shown in green is the location of the NASA IV&V facility (NASA-IVV-JSTAR) where the STF-1 mission operations center (MOC) is located. During a typical contact, the MOC connects to the WFF antenna facility over the NASA network and routes commands to WFF and up to STF-1 through the antenna and receives telemetry down through the WFF antenna and back to the STF-1 MOC over the NASA network.

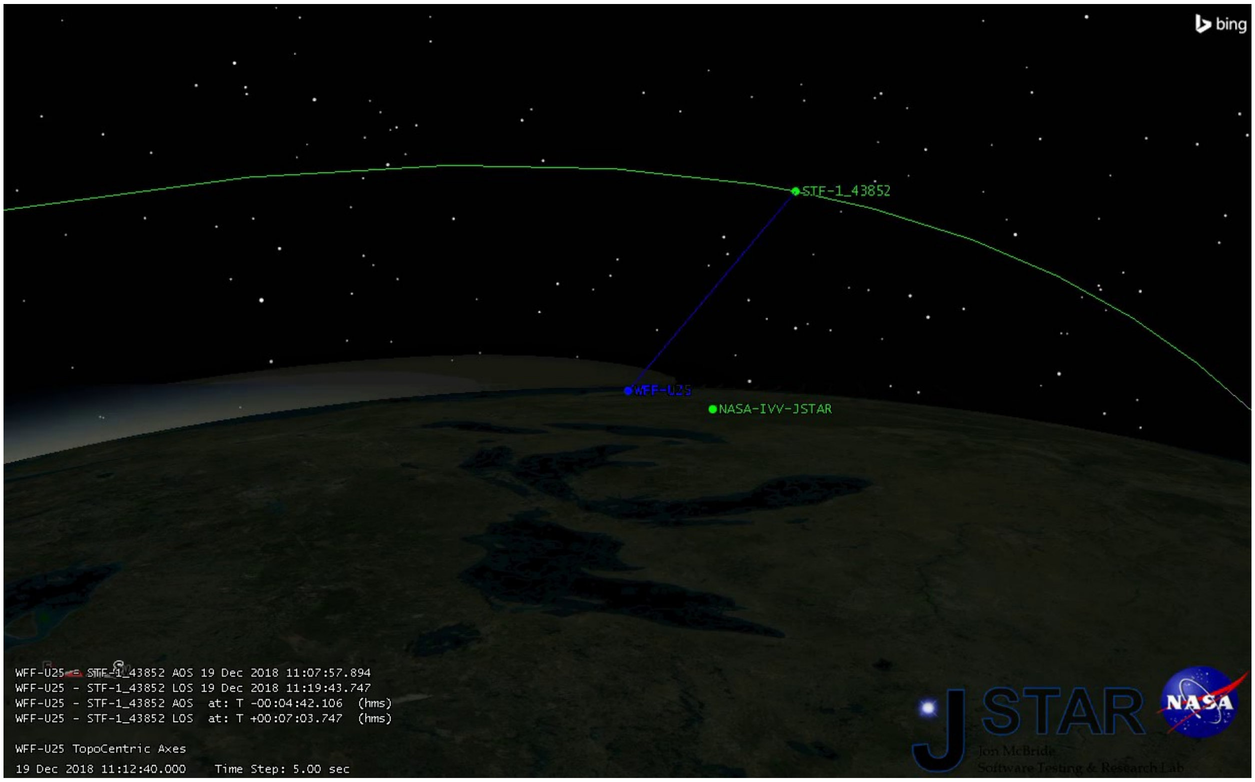


Figure 2: STK Visualization of First Contact

Following initial contact with STF-1 on December 16, 2019, contact was made several more times in the next several weeks before absolutely confirming that USSTRATCOM TLE satellite number 43852 was STF-1. During that time, STK was used to generate numerous other scenarios to evaluate satellite number 43852 and the other satellite numbers from the ELaNa XIX mission as part of the positive identification process.

After positive identification, STF-1 began the commissioning phase and operations fell into a more routine cycle. The remainder of the paper describes some of the tools used for automating those operations.

PLANNING

As mentioned previously, the WFF antenna supports several missions besides STF-1. In order to plan and support these missions, WFF uses a weekly planning process for assessing the satellite inviews for the following week and assigning contact times. Planned weeks run from Monday through Sunday. The planning process has the following timeline. On Monday or Tuesday of each week, a draft schedule is published from WFF to all of the satellite operators for the following week. After accepting comments and requests from the satellite operators, a final schedule is published on Thursday or Friday for the following week. As the operating week progresses, occasionally schedule changes become necessary and updated schedules are published as needed. Figure 3 below shows a line from a WFF published schedule for the STF-1 satellite. Note that the schedule indicates the date of the inview, the start and end of the inview (i.e. when the satellite is above the horizon) in both Greenwich Mean Time (GMT) and local time (L), which is United States Eastern Time, the duration of the inview time, whether WFF plans to support the inview or not, and the maximum elevation angle between the WFF antenna and the satellite.

6	Version	Final Rev 0				Weekly Schedule for:		13-May-19	
7	Date (GMT)	Mission	Start (GMT)	End (GMT)	Max Elev	Start (L)	End (L)	Duration	Support
35	13-May-19	stf1	18:56	19:07	60.9	14:56	15:07	0:11:36	Y

Figure 3: WFF Schedule Excerpt

While the WFF schedule contains all of the crucial information for planning satellite MOC operations, there has been a desire by the STF-1 operations team to view additional data and in a more graphical format. This led to the creation of the Orbit, Inview, and Power Planning (OIPP) tool. This tool is executed daily after retrieving the latest two-line element set for STF-1. It generates an HTML report that the STF-1 team can access on-line. This report shows timelines for the current and future days in STF-1 MOC local time, which is U.S. Eastern Time. The basic report indicates the satellite being reported, the date of the report, the two-line element set data used, and the ground station(s) for which inviews and schedule information is reported. Under that information, timelines are displayed. Each timeline displays a bar for the entire day with the day/time information on it. For the current day, a bar is shown indicating when the report was generated. Following that are timelines showing when the satellite is inview of the specified ground stations. Each timeline bar represents an inview. The timeline bars are color coded according to additional information available. Gray indicates inview only, i.e. no schedule information is available. Purple indicates that schedule information is available, but antenna support has not been assigned for this inview. Blue indicates that schedule information is available and the antenna (WFF antenna in the STF-1 case) has been assigned to provide contact and support STF-1 during the inview. Finally, a timeline is displayed showing when the satellite is in sunlight, penumbra, and umbra. The display provides an at-a-glance view of the upcoming contacts for STF-1 with the WFF antenna over the upcoming days. Note that the user can hover over each timeline bar to display a pop-up with specific time information for the bar (e.g. exact inview times, sunlight times, whether contact has been assigned or not, etc.) Figure 4 below shows the OIPP report (current reports are available at http://www.stf1.com/stf1_wff.php).

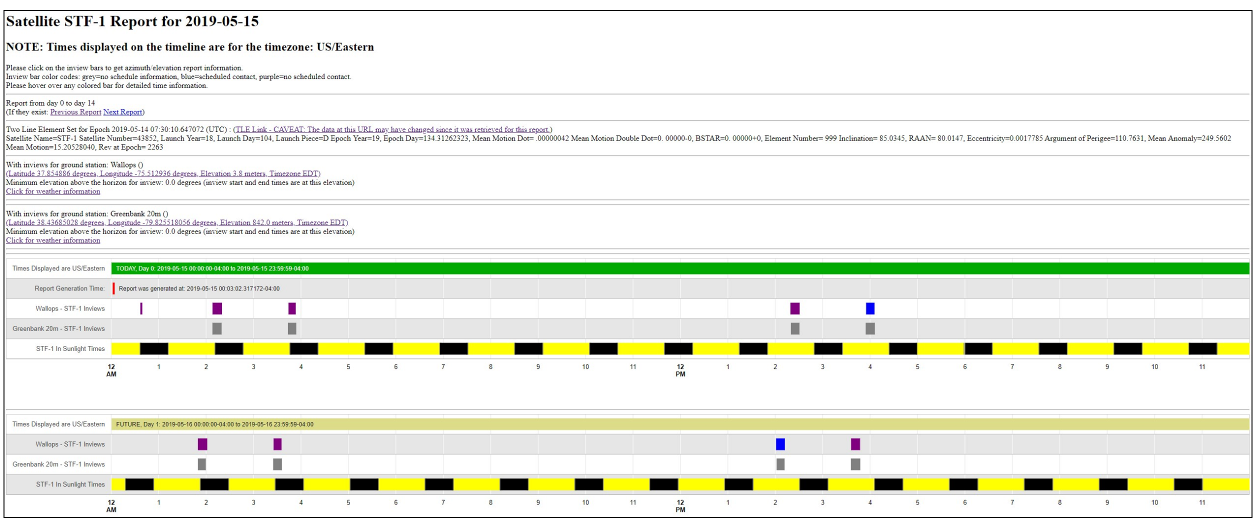
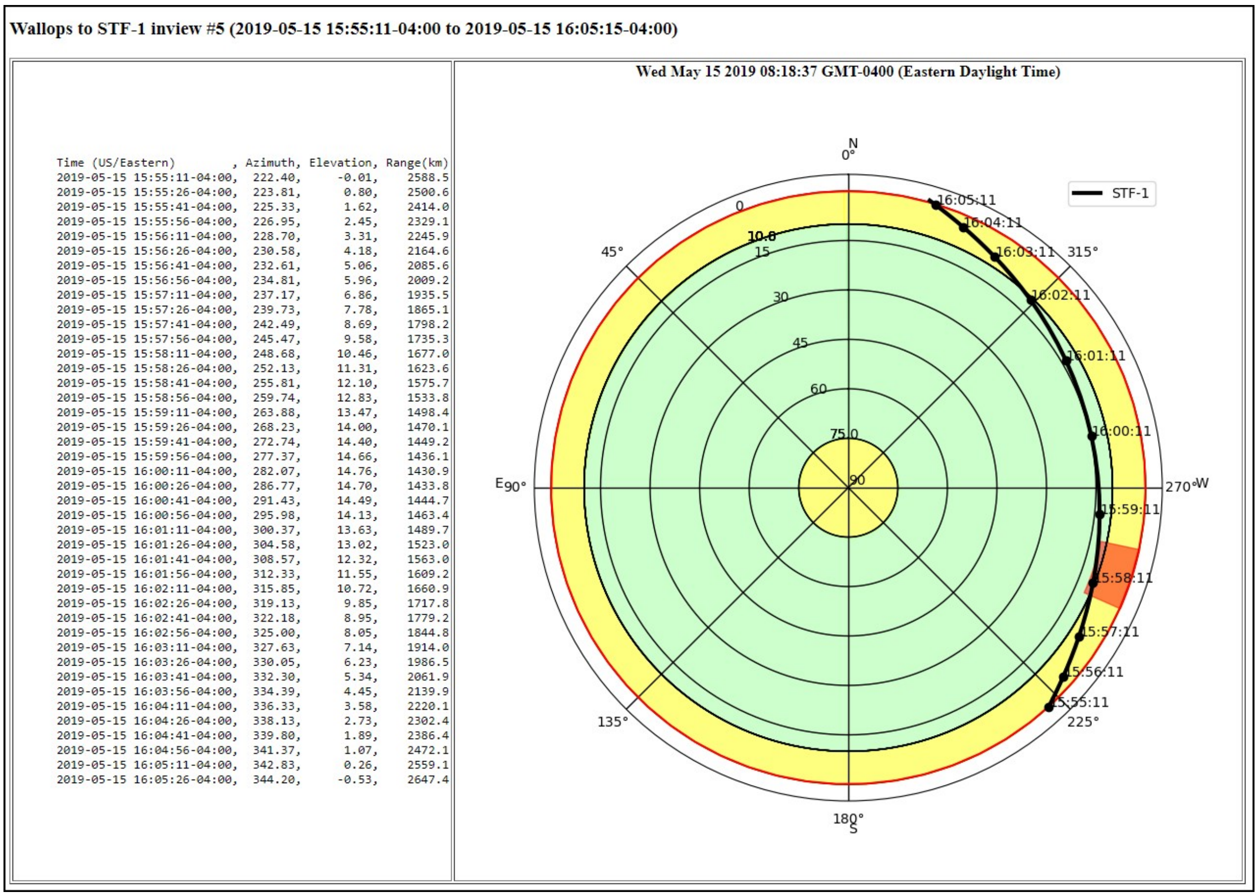


Figure 4: OIPP Report

As STF-1 proceeded with operations, it became apparent that certain elevation passes and certain direction passes (to the east vs. to the west; north to south vs. south to north) were more conducive for communications. Based on that, OIPP was enhanced so that inview bars could be clicked and a new page shown. This new page would show azimuth, elevation, and range data from the ground station to the satellite for each inview between the ground station and the satellite on the day of the inview and would be automatically positioned to have the selected inview scrolled to be displayed. Figure 5 below shows an example of the azimuth, elevation, and range page. It can be seen that at the top is a line indicating the ground station, satellite, inview number for the day and the inview start and stop times. Below that line and to the left is a tabular display of time, azimuth, elevation, and range data which is reported every 15 seconds. Below the top line and to the right is a graphical display of the same information. This graph shows rings which represent various elevation angles. The red outer ring is at 0-degree elevation (the horizon). The center of the bullseye represents 90-degree elevation, or directly overhead. This display is intended to be a sky chart (vs. a map), so the azimuth angle is shown with 0 degrees or north at the top, 90 degrees or east at the left, 180 degrees or south at the bottom, and 270 degrees or west at the right. Several other static features are also shown on the display based on configuration information. At some azimuths and elevations, communication is usually not very good, so these areas are shaded in yellow or red, whereas azimuth and elevation areas that tend to have better communication (based on past experience) are shaded in green. These are statically defined, and do not represent hard boundaries of communication, rather they are indicators to the STF-1 MOC operator of guidelines for communication regions. On top of this static graphical information, a black line indicates the track of the satellite in azimuth and elevation over time. The track also has points at various times to indicate when the satellite will be at various azimuths and elevations. Finally, while shown statically because this is a picture, the time information above the graph updates automatically when the user is viewing the web page so that the user knows what time it currently is and can then use that to gauge approximately where on the graph the satellite currently is located.


Wallops to STF-1 inview #5 (2019-05-15 15:55:11-04:00 to 2019-05-15 16:05:15-04:00)

Time (US/Eastern)	Azimuth	Elevation	Range(km)
2019-05-15 15:55:11-04:00	222.40	-0.01	2588.5
2019-05-15 15:55:26-04:00	223.81	0.80	2500.6
2019-05-15 15:55:41-04:00	225.33	1.62	2414.0
2019-05-15 15:55:56-04:00	226.95	2.45	2329.1
2019-05-15 15:56:11-04:00	228.70	3.31	2245.9
2019-05-15 15:56:26-04:00	230.58	4.18	2164.6
2019-05-15 15:56:41-04:00	232.61	5.06	2085.6
2019-05-15 15:56:56-04:00	234.81	5.96	2009.2
2019-05-15 15:57:11-04:00	237.17	6.86	1935.5
2019-05-15 15:57:26-04:00	239.73	7.78	1865.1
2019-05-15 15:57:41-04:00	242.49	8.69	1798.2
2019-05-15 15:57:56-04:00	245.47	9.58	1735.3
2019-05-15 15:58:11-04:00	248.68	10.46	1677.0
2019-05-15 15:58:26-04:00	252.13	11.31	1623.6
2019-05-15 15:58:41-04:00	255.81	12.10	1575.7
2019-05-15 15:58:56-04:00	259.74	12.83	1533.8
2019-05-15 15:59:11-04:00	263.88	13.47	1498.4
2019-05-15 15:59:26-04:00	268.23	14.00	1470.1
2019-05-15 15:59:41-04:00	272.74	14.40	1449.2
2019-05-15 15:59:56-04:00	277.37	14.66	1436.1
2019-05-15 16:00:11-04:00	282.07	14.76	1430.9
2019-05-15 16:00:26-04:00	286.77	14.70	1433.8
2019-05-15 16:00:41-04:00	291.43	14.49	1444.7
2019-05-15 16:00:56-04:00	295.98	14.13	1463.4
2019-05-15 16:01:11-04:00	300.37	13.63	1489.7
2019-05-15 16:01:26-04:00	304.58	13.02	1523.0
2019-05-15 16:01:41-04:00	308.57	12.32	1563.0
2019-05-15 16:01:56-04:00	312.33	11.55	1609.2
2019-05-15 16:02:11-04:00	315.85	10.72	1660.9
2019-05-15 16:02:26-04:00	319.13	9.85	1717.8
2019-05-15 16:02:41-04:00	322.18	8.95	1779.2
2019-05-15 16:02:56-04:00	325.00	8.05	1844.8
2019-05-15 16:03:11-04:00	327.63	7.14	1914.0
2019-05-15 16:03:26-04:00	330.05	6.23	1986.5
2019-05-15 16:03:41-04:00	332.30	5.34	2061.9
2019-05-15 16:03:56-04:00	334.39	4.45	2139.9
2019-05-15 16:04:11-04:00	336.33	3.58	2220.1
2019-05-15 16:04:26-04:00	338.13	2.73	2302.4
2019-05-15 16:04:41-04:00	339.80	1.89	2386.4
2019-05-15 16:04:56-04:00	341.37	1.07	2472.1
2019-05-15 16:05:11-04:00	342.83	0.26	2559.1
2019-05-15 16:05:26-04:00	344.20	-0.53	2647.4

Figure 5: Azimuth/Elevation Pass Prediction

OPERATIONS

A few minutes prior to an assigned STF-1 contact, the STF-1 operator contacts the WFF antenna operators via telephone. During the time prior to inview start, the operators exchange information about inview start (AOS, or acquisition of signal), inview end (LOS, or loss of signal), and maximum elevation of the pass. In addition, prior to pass start, the STF-1 operator sends a test command. The WFF antenna operators report if the command was received, and if so, what the frequency and power level of the command was. This is to ensure that all of the equipment is properly connected and configured to support the pass.

Once the pass begins, the MOC operator coordinates with the antenna operators so that the antenna operator can report when the antenna has reached the elevation angle that the MOC operator wishes to begin commanding. The MOC operator uses the open source COSMOS command and control system from Ball Aerospace for sending commands and receiving telemetry from STF-1. This same system was used during development of STF-1, both in the software only simulation (NOS[3]) and in testing the actual flight hardware and software prior to launch. Figure 6 below shows the COSMOS interface. To the right of the "CADET_INT" interface, the operator can see the number of command packets and bytes transmitted and the number of telemetry packets and bytes received. In addition, the command sender interface is shown, where the operator selects and configures a command and its parameters to send (in this case "MGR_SET_NVRAM_SPW_1_TOGGLE", a request for the Cadet radio on STF-1 to transmit data that has been stored on it).

Each time the MOC operator sends a command via the interface, the operator states verbally that the command has been sent. The antenna operator verbally confirms that they see the transmission of the command on the signal analyzer at the antenna and can confirm frequency and power level when requested. Following that, if data is received from the spacecraft, the antenna operator reports that a data signal was seen on the spectrum analyzer, what the power level was, and if there was any variation of the power level during the receipt of data. Variation of power level indicates tumbling of the satellite. This helps the MOC operator assess how good the signal and resulting data in the telemetry might be and provides feedback for determining when to send the next command.

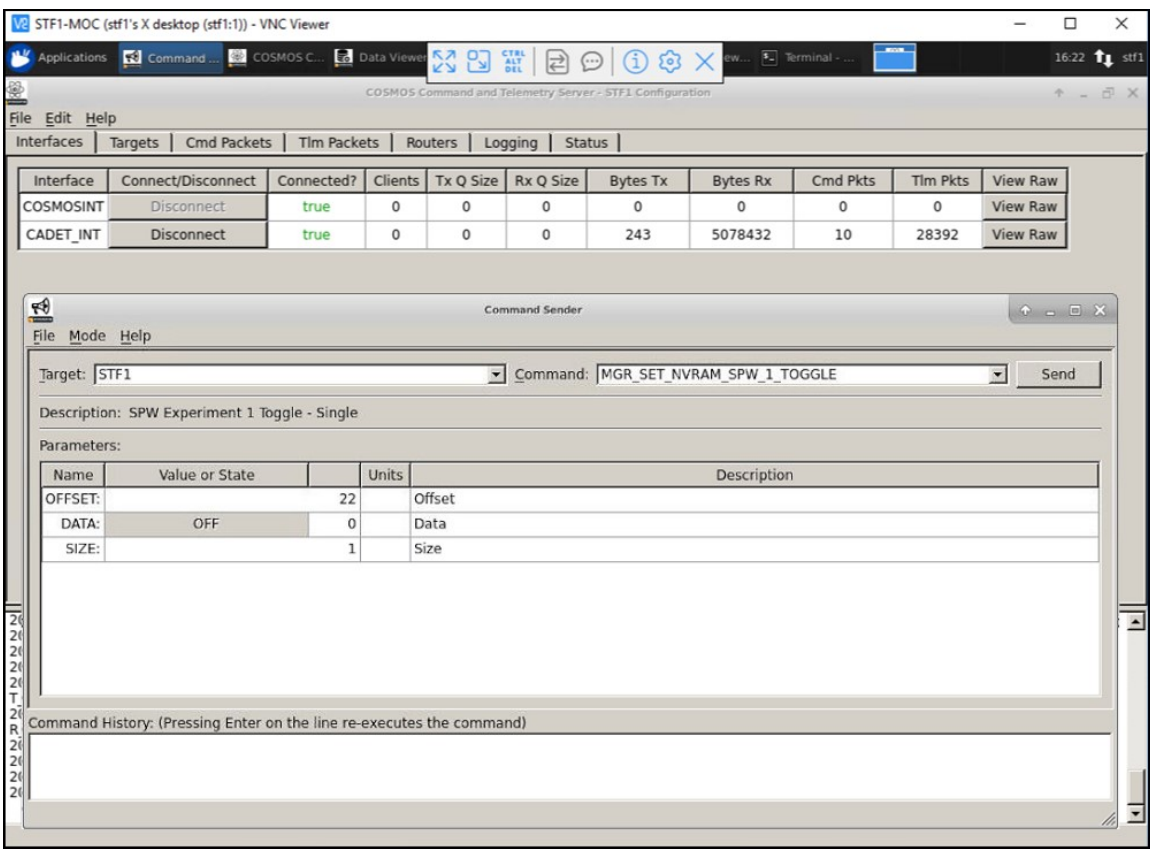


Figure 6: COSMOS Command and Control Interface

POST PASS PROCESSING

A few minutes after the end of each pass, a number of programs run automatically on the STF-1 retrieval, archival, and processing (RAP) server. During an operations contact, the MOC computer records the commands and telemetry for the contact. In addition, the telemetry is forwarded from the MOC computer to the RAP server over the network where the RAP server also records the telemetry. This telemetry is all in binary form. The programs that are automatically run after the contact process the binary data into more readable human forms.

One product of these automated runs is a graph similar to the azimuth and elevation graph described in planning section. However, this time, the graph is overlaid with dots showing where (in azimuth and elevation) the spacecraft was when commands were sent to the spacecraft and when telemetry was received from the spacecraft. Figure 7 below shows this graph. It should also be noted that this graph is automatically distributed to the STF-1 team using the Slack messaging program so that it is immediately available. This graph helps the team with understanding the communication success/failure at different azimuths and elevations. It has been noticed that there are definitely better and worse regions of azimuth/elevation and directionality (east vs. west, north to south vs. south to north) for communications and these graphs help depict this information automatically after every contact to the STF-1 team.

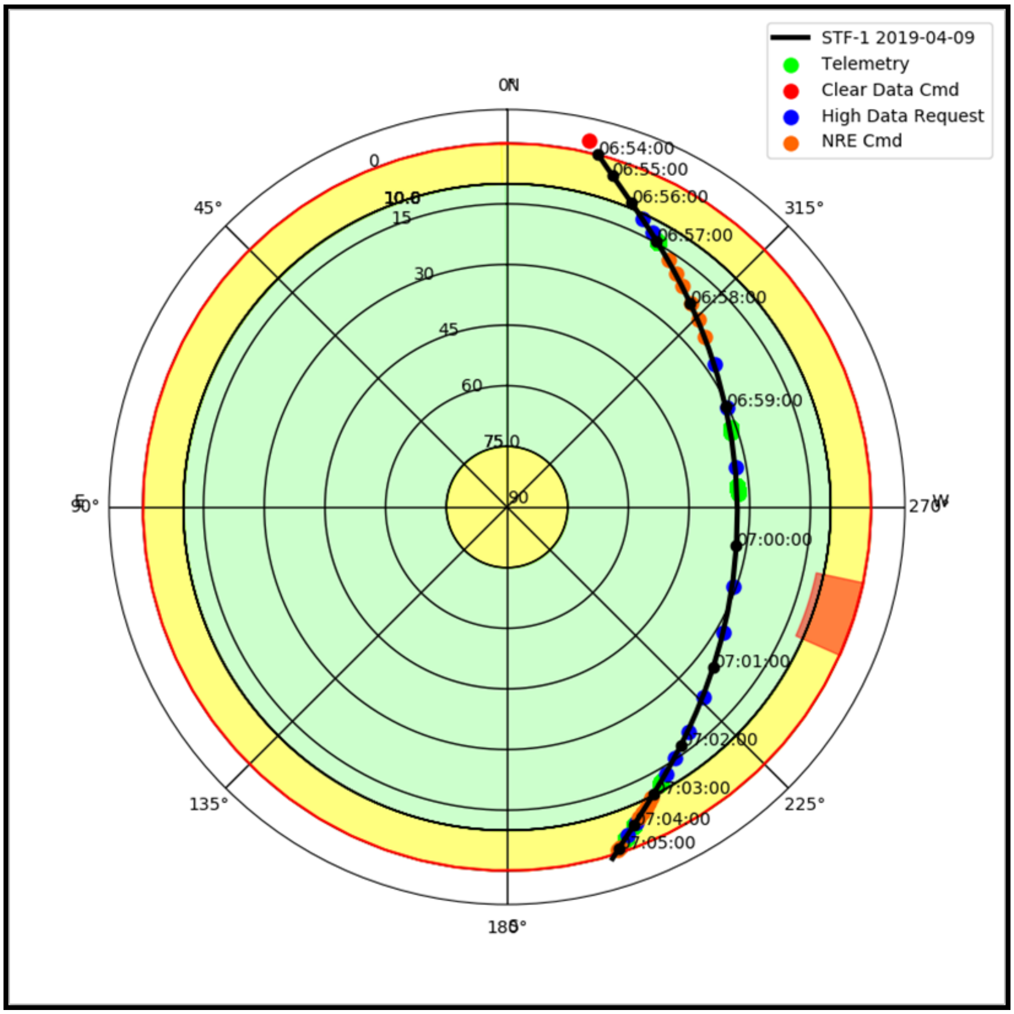


Figure 7: Azimuth/Elevation Post-Contact Command and Telemetry Graph

Another product automatically generated on the RAP server immediately after every pass is a summary of a few lines of key health and safety telemetry and a summary of commands for the pass. The command summary reports all commands that turn experiments on and off, but only reports once a request for high (important health) telemetry data from the radio buffers and once a request for low (experiment) telemetry data from the radio buffers since those are usually requested multiple times each pass. This data is also posted automatically to Slack for the STF-1 team to immediately see and review. The intent is to provide key, dashboard type information such as the temperature of and space usage on the Cadet radio and the electrical power system voltage and expected/actual switch states. In addition, STF-1 has a manager software application that manages the core state of the satellite, including what experiments are currently running, etc. Important telemetry from this application is also reported and includes what mission phase the satellite is in (currently always 4, or operational), how many power-on resets the computer has experienced, and how many times each experiment has run. An example of this data, as shown in slack, is provided in Figure 8 below.

stf1-rap APP 3:12 PM

```
TARGET,PACKET,CCSDS_SECONDS,STATUSINFO_TIME,SECONDSUP,STF1_FIFO,RECEIVED_TIMEFORMATTED,STATUSINFO_STORAGESPACEFREE,STATUSINFO_LOFIFOUSAGE,STATUSINFO_HIFIFOUSAGE,STATUSINFO_TEMPERATURE,
STF1_TLM,CADET_HK_TLM_T,72711849,21380343,1470425090,65,2019/05/13 14:59:34.817,3392385279,666202112,968704,17
STF1_TLM,CADET_HK_TLM_T,6105227,4597986,4596834,65,2019/05/13 14:59:32.281,3394208127,665255936,616448,61
STF1_TLM,CADET_HK_TLM_T,5602994,4603017,4601865,65,2019/05/13 14:59:34.767,3459535359,666185728,948224,65527
STF1_TLM,CADET_HK_TLM_T,5602839,12990575,4600814,65,2019/05/13 14:59:34.276,3392811519,665989120,755712,65480
STF1_TLM,CADET_HK_TLM_T,5602615,4602776,4601614,65,2019/05/13 14:59:34.639,3929387519,666136576,903168,65517
```

```
TARGET,PACKET,CCSDS_SECONDS,STF1_FIFO,RECEIVED_TIMEFORMATTED,VIDIODE,PDM_STATES_EXPECTED,PDM_STATES_ACTUAL,
STF1_TLM,EPS_HK_TLM_T,5730014,65,2019/05/13 14:59:32.769,8.2628173828125,0,0
STF1_TLM,EPS_HK_TLM_T,5602964,65,2019/05/13 14:59:34.815,8.253817558288574,0,0
STF1_TLM,EPS_HK_TLM_T,5602624,65,2019/05/13 14:59:34.640,8.753817558288574,0,0
STF1_TLM,EPS_HK_TLM_T,5602174,65,2019/05/13 14:59:34.413,8.2628173828125,0,0
STF1_TLM,EPS_HK_TLM_T,5601944,65,2019/05/13 14:59:34.324,8.253817558288574,0,0
```

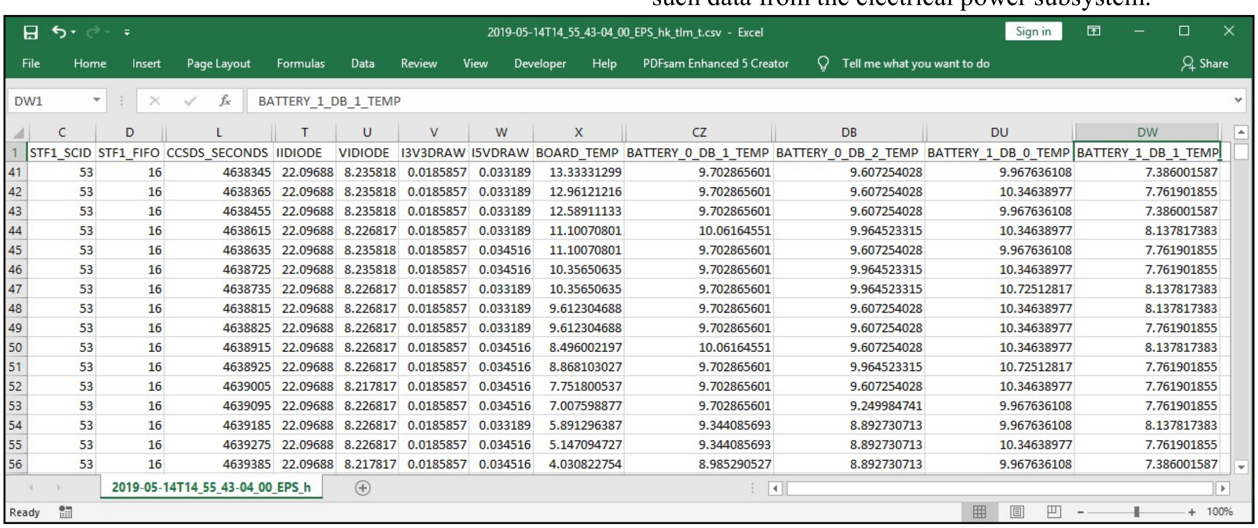
```
TARGET,PACKET,CCSDS_SECONDS,NVRAM_TOTAL_ELAPSED_TIME,STF1_FIFO,RECEIVED_TIMEFORMATTED,NVRAM_MISSION_PHASE,NVRAM_POR_CNTR,NVRAM_EXPERIMENTS_0_IS_VALID,NVRAM_EXPERIMENTS_0_SUCCESS_CTR,NVRAM_EXPERIMENTS
_1_IS_VALID,NVRAM_EXPERIMENTS_1_SUCCESS_CTR,NVRAM_EXPERIMENTS_2_IS_VALID,NVRAM_EXPERIMENTS_2_SUCCESS_CTR,NVRAM_EXPERIMENTS_3_IS_VALID,NVRAM_EXPERIMENTS_3_SUCCESS_CTR,NVRAM_EXPERIMENTS_4_IS_VALID,NVRA
M_EXPERIMENTS_4_SUCCESS_CTR,NVRAM_EXPERIMENTS_5_IS_VALID,NVRAM_EXPERIMENTS_5_SUCCESS_CTR,NVRAM_EXPERIMENTS_6_IS_VALID,NVRAM_EXPERIMENTS_6_SUCCESS_CTR,NVRAM_EXPERIMENTS_7_IS_VALID,NVRAM_EXPERIMENTS_7_
SUCCESS_CTR,NVRAM_EXPERIMENTS_8_IS_VALID,NVRAM_EXPERIMENTS_8_SUCCESS_CTR,
STF1_TLM,MGR_HK_TLM_T,696444202,288221206,65,2019/05/13 14:59:34.324,-258497678,29542186,103,2605426697,122,216916406,234,147909085,70,1040094319,175,2052391051,0,150994944,2,0,3,7208960,5,5
STF1_TLM,MGR_HK_TLM_T,5634072,147041788,65,2019/05/13 14:59:33.990,524292,9,2,58,0,617,0,2147746629,0,1434,0,8,0,2,0,1024,0,11,0,575
STF1_TLM,MGR_HK_TLM_T,5602994,12825750,65,2019/05/13 14:59:34.856,4,9,0,262202,0,616,0,837,0,1434,0,8,0,2,0,0,0,11,0,575
STF1_TLM,MGR_HK_TLM_T,5602976,12825740,65,2019/05/13 14:59:34.817,4,9,2,58,0,3462332416,64,3462332416,0,0,220,80,141,4081124367,151,1964851604,64,268622915,117,3217671056
STF1_TLM,MGR_HK_TLM_T,5602864,12825620,65,2019/05/13 14:59:34.767,536870916,9,0,58,0,617,64,837,0,1426,0,8,2,3,0,0,0,11,0,703
```

```
2019/05/13 14:59:24.542  cmd("STF1 CADET_FIFO_REQUEST_CC with FLAGS HIGH FIFO, PACKET_COUNT 2000, STARTING_PACKET 0, NEW_PACKET_SIZE 0, XMIT_PWR_LEVEL 1")
```

Figure 8: Slack Key Command and Telemetry Messages

DATA PROCESSING

At the same time that the quick post pass assessment data is generated, several other processes are also executed to generate full human readable data for later analysis by the STF-1 operations team and the STF-1 science teams. First, all binary telemetry is processed into comma separated value (CSV) format files for analysis. Figure 9 below shows an example of some such data from the electrical power subsystem.



	C	D	L	T	U	V	W	X	CZ	DB	DU	DW
1	STF1_SCID	STF1_FIFO	CCSDS_SECONDS	IIDIODE	VIDIODE	I3V3DRAW	I5VDRAW	BOARD_TEMP	BATTERY_0_DB_1_TEMP	BATTERY_0_DB_2_TEMP	BATTERY_1_DB_0_TEMP	BATTERY_1_DB_1_TEMP
41	53	16	4638345	22.09688	8.235818	0.0185857	0.033189	13.33331299	9.702865601	9.607254028	9.967636108	7.386001587
42	53	16	4638365	22.09688	8.235818	0.0185857	0.033189	12.96121216	9.702865601	9.607254028	10.34638977	7.761901855
43	53	16	4638455	22.09688	8.235818	0.0185857	0.033189	12.58911133	9.702865601	9.607254028	9.967636108	7.386001587
44	53	16	4638615	22.09688	8.226817	0.0185857	0.033189	11.10070801	10.06164551	9.964523315	10.34638977	8.137817383
45	53	16	4638635	22.09688	8.235818	0.0185857	0.034516	11.10070801	9.702865601	9.607254028	9.967636108	7.761901855
46	53	16	4638725	22.09688	8.235818	0.0185857	0.034516	10.35650635	9.702865601	9.964523315	10.34638977	7.761901855
47	53	16	4638735	22.09688	8.226817	0.0185857	0.033189	10.35650635	9.702865601	9.964523315	10.72512817	8.137817383
48	53	16	4638815	22.09688	8.226817	0.0185857	0.033189	9.612304688	9.702865601	9.607254028	10.34638977	8.137817383
49	53	16	4638825	22.09688	8.226817	0.0185857	0.033189	9.612304688	9.702865601	9.607254028	10.34638977	7.761901855
50	53	16	4638915	22.09688	8.226817	0.0185857	0.034516	8.496002197	10.06164551	9.607254028	10.34638977	8.137817383
51	53	16	4638925	22.09688	8.226817	0.0185857	0.034516	8.868103027	9.702865601	9.964523315	10.72512817	7.761901855
52	53	16	4639005	22.09688	8.217817	0.0185857	0.034516	7.751800537	9.702865601	9.607254028	10.34638977	7.761901855
53	53	16	4639095	22.09688	8.226817	0.0185857	0.034516	7.007598877	9.702865601	9.249984741	9.967636108	7.761901855
54	53	16	4639185	22.09688	8.226817	0.0185857	0.033189	5.891296387	9.344085693	8.892730713	9.967636108	8.137817383
55	53	16	4639275	22.09688	8.226817	0.0185857	0.034516	5.147094727	9.344085693	8.892730713	10.34638977	7.761901855
56	53	16	4639385	22.09688	8.217817	0.0185857	0.034516	4.030822754	8.985290527	8.892730713	9.967636108	7.386001587

Figure 9: Electrical Power System Telemetry in CSV Format

The following is a list of all telemetry data produced by STF-1. This data is all automatically captured in binary form on the MOC and the RAP and is also processed into CSV form on the RAP server:

1. Core Flight Executive telemetry
   a. Executive services
   b. Event messages
   c. Event services telemetry
   d. Software bus telemetry
   e. Time services
2. STF-1 specific software applications
   a. Manager
   b. Electrical power system
   c. Cadet radio
   d. Single board computer sensors (IMU, magnetometer, temperature)
3. Experiments
   a. Camera housekeeping and experiment
   b. CSEE housekeeping, experiment 1 and experiment 2
   c. GPS housekeeping, time, position, velocity, science 1 and science 2
   d. IMU housekeeping, streaming, and SD card
   e. SPW housekeeping, Geiger counter and Langmuir probe

In addition to the processing that occurs after each pass, some processing is performed daily in order to provide insight into the performance of STF-1. Figures 10, 11, and 12 show some of the automated graphs that are produced daily.

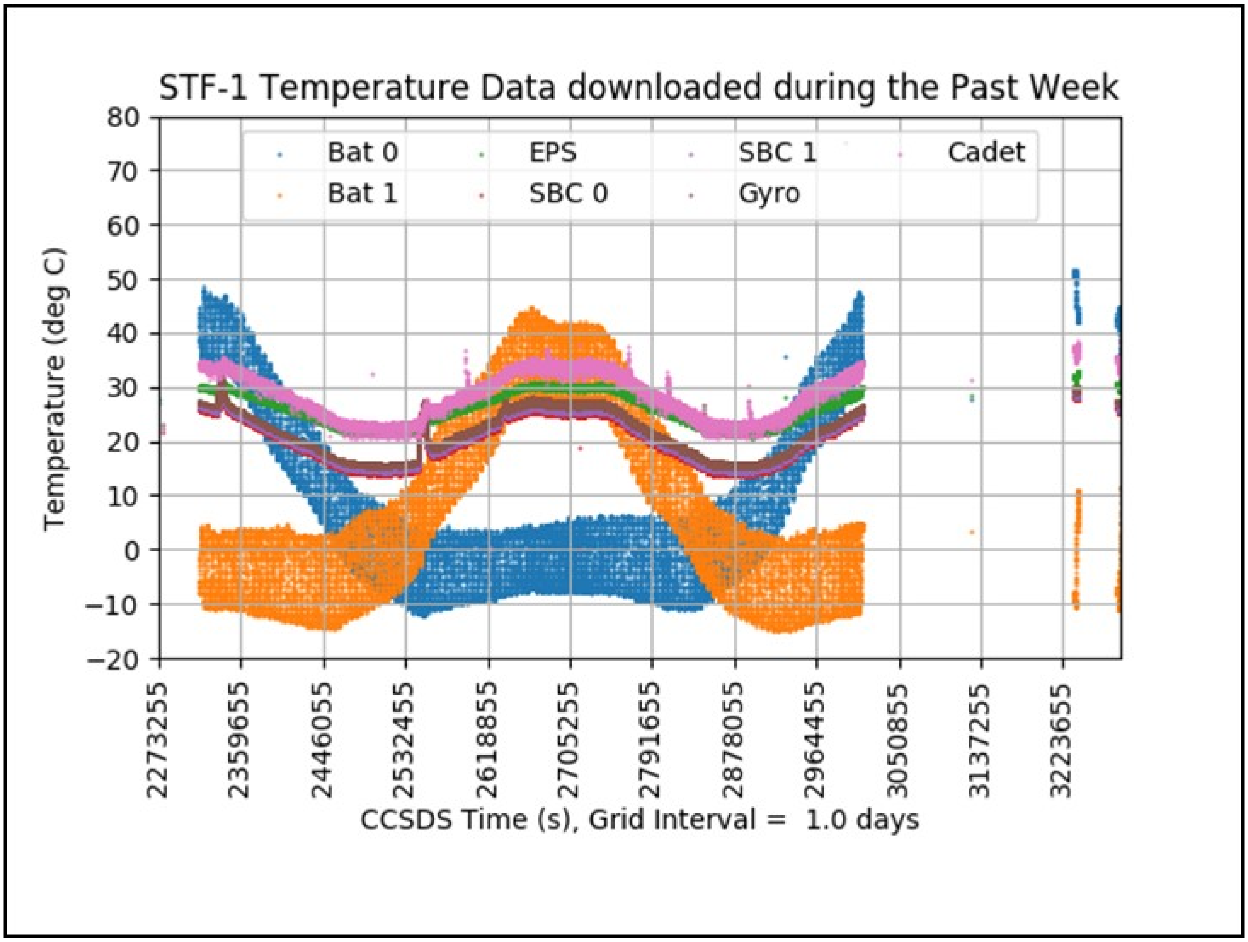


Figure 10: STF-1 Temperature Sensor Graphs

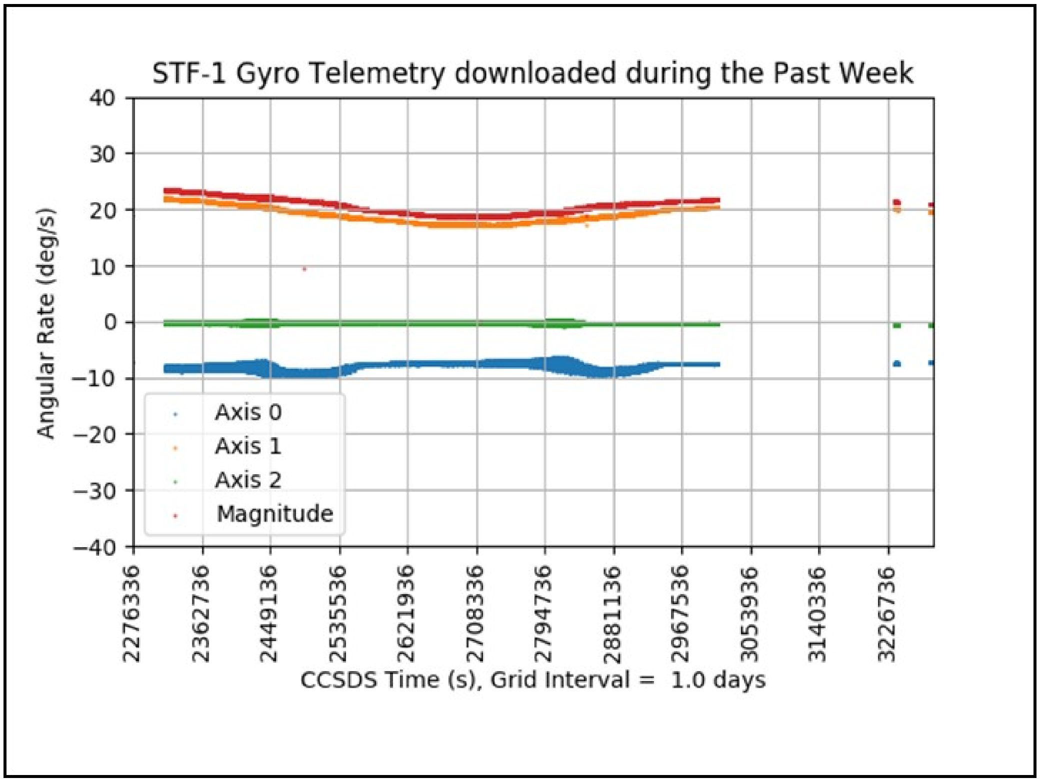


Figure 11: STF-1 Gyroscope Sensor Graphs

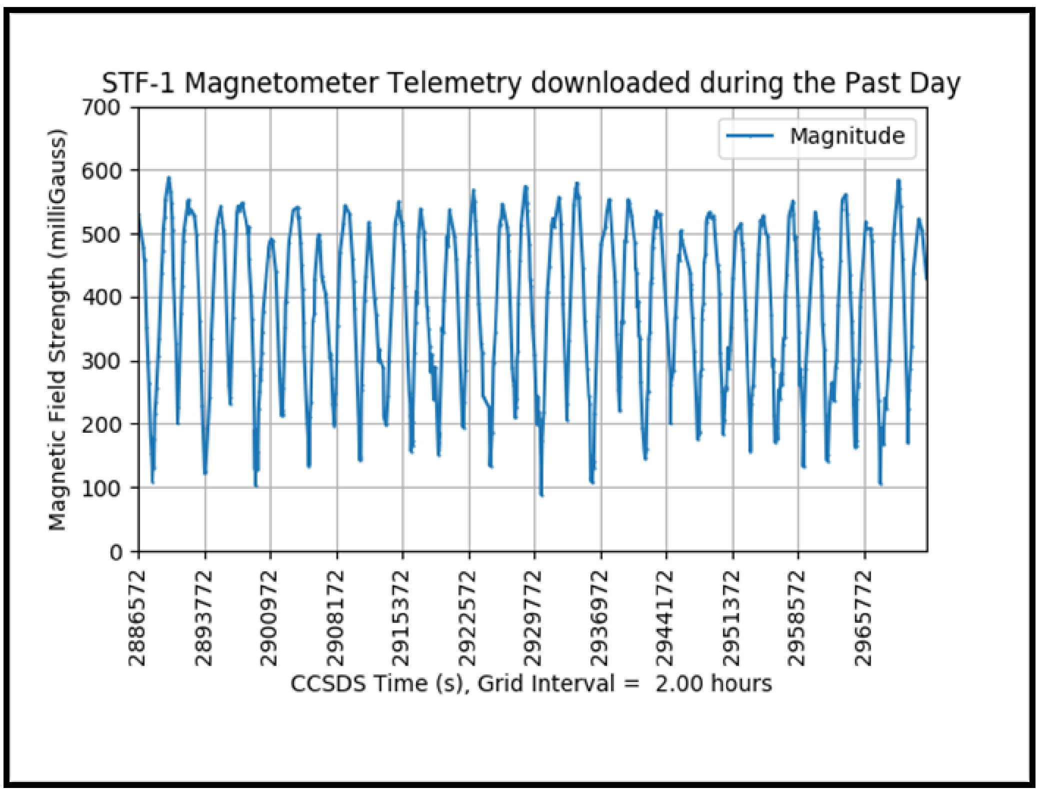
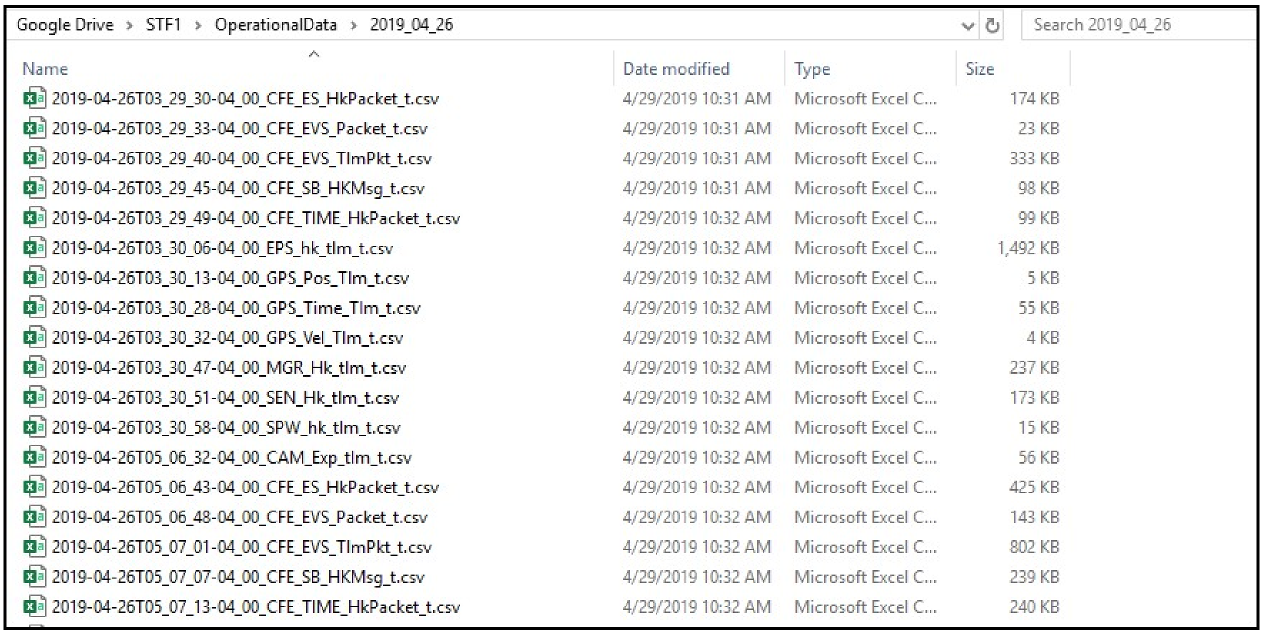


Figure 12: STF-1 Magnetometer Sensor Graph

As was noted, each of these graphs is generated automatically. Also, there are bit flips in the data due to the nature of the communication link, so some automatic filtering of bad data is being performed prior to generating these graphs.

DATA DISTRIBUTION

In addition to automatically processing the STF-1 telemetry, the resulting human readable CSV files must be made available to the STF-1 operations team and the STF-1 science teams for further analysis. One technique to facilitate this information sharing is for the RAP server to automatically upload the CSV telemetry files to a shared Google drive for access by the various teams. The drive has a folder called OperationalData where processed telemetry is stored. Under this folder, a dated folder is created for each date and the processed telemetry automatically uploaded. Figure 13 shows a portion of the contents of the Google drive folder for April 26, 2019.


Google Drive > STF1 > OperationalData > 2019_04_26   Search 2019_04_26

Name	Date modified	Type	Size
2019-04-26T03_29_30-04_00_CFE_ES_HkPacket_t.csv	4/29/2019 10:31 AM	Microsoft Excel C...	174 KB
2019-04-26T03_29_33-04_00_CFE_EVS_Packet_t.csv	4/29/2019 10:31 AM	Microsoft Excel C...	23 KB
2019-04-26T03_29_40-04_00_CFE_EVS_TlmPkt_t.csv	4/29/2019 10:31 AM	Microsoft Excel C...	333 KB
2019-04-26T03_29_45-04_00_CFE_SB_HKMsg_t.csv	4/29/2019 10:31 AM	Microsoft Excel C...	98 KB
2019-04-26T03_29_49-04_00_CFE_TIME_HkPacket_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	99 KB
2019-04-26T03_30_06-04_00_EPS_hk_tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	1,492 KB
2019-04-26T03_30_13-04_00_GPS_Pos_Tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	5 KB
2019-04-26T03_30_28-04_00_GPS_Time_Tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	55 KB
2019-04-26T03_30_32-04_00_GPS_Vel_Tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	4 KB
2019-04-26T03_30_47-04_00_MGR_Hk_tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	237 KB
2019-04-26T03_30_51-04_00_SEN_Hk_tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	173 KB
2019-04-26T03_30_58-04_00_SPW_hk_tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	15 KB
2019-04-26T05_06_32-04_00_CAM_Exp_tlm_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	56 KB
2019-04-26T05_06_43-04_00_CFE_ES_HkPacket_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	425 KB
2019-04-26T05_06_48-04_00_CFE_EVS_Packet_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	143 KB
2019-04-26T05_07_01-04_00_CFE_EVS_TlmPkt_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	802 KB
2019-04-26T05_07_07-04_00_CFE_SB_HKMsg_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	239 KB
2019-04-26T05_07_13-04_00_CFE_TIME_HkPacket_t.csv	4/29/2019 10:32 AM	Microsoft Excel C...	240 KB

Figure 13: Google Drive Folder of Shared STF-1 Telemetry

Finally, there is a need to visualize at a glance when experiments have been executed and when telemetry from these experiments has been downlinked and processed. Scripts have been created on the RAP server that can automatically process the command files and examine the telemetry directories and produce a block calendar style view in HTML of when experiments were executed and when downlinked experiment telemetry was processed. Figure 14 shows a block calendar view for the experiments executed and downlinked telemetry processed during April 2019.

April 2019						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3 2019-04-03T19_43_25-04_00_CSEE_exp1_tlm_t.csv 2019-04-03T19_44_45-04_00_GPS_Time_Tlm_t.csv	4	5 SPW_1 SPW_2 GPS_1	6
7	8 GPS_2	9 CSEE_1 CSEE_2	10 CAM	11 2019-04-11T06_33_35-04_00_CAM_Exp_tlm_t.csv	12 2019-04-12T06_17_58-04_00_SPW_geiger_tlm_t.csv 2019-04-12T06_18_07-04_00_SPW_lp_tlm_t.csv 2019-04-12T06_17_19-04_00_GPS_Time_Tlm_t.csv	13
14	15	16 2019-04-16T06_36_29-04_00_GPS_Sci1_Tlm_t.csv 2019-04-16T06_36_33-04_00_GPS_Sci2_Tlm_t.csv 2019-04-16T06_36_37-04_00_GPS_Time_Tlm_t.csv	17 CAM	18 2019-04-18T05_59_17-04_00_CAM_Exp_tlm_t.csv 2019-04-18T18_10_27-04_00_CAM_Exp_tlm_t.csv 2019-04-18T19_43_20-04_00_CAM_Exp_tlm_t.csv	19	20
21	22 SPW_1 GPS_1	23 CSEE_1 CAM SPW_2 GPS_1	24 2019-04-24T05_46_20-04_00_SPW_geiger_tlm_t.csv 2019-04-24T05_46_32-04_00_SPW_lp_tlm_t.csv 2019-04-24T17_57_47-04_00_SPW_geiger_tlm_t.csv 2019-04-24T17_58_00-04_00_SPW_lp_tlm_t.csv 2019-04-24T05_45_25-04_00_GPS_Time_Tlm_t.csv 2019-04-24T17_57_00-04_00_GPS_Time_Tlm_t.csv	25 CAM GPS_1 2019-04-25T17_36_36-04_00_GPS_Time_Tlm_t.csv	26 2019-04-26T05_06_32-04_00_CAM_Exp_tlm_t.csv 2019-04-26T03_30_28-04_00_GPS_Time_Tlm_t.csv 2019-04-26T05_08_08-04_00_GPS_Time_Tlm_t.csv 2019-04-26T15_41_24-04_00_GPS_Time_Tlm_t.csv	27
28	29 2019-04-29T16_21_28-04_00_CAM_Exp_tlm_t.csv 2019-04-29T17_56_41-04_00_CAM_Exp_tlm_t.csv 2019-04-29T16_22_53-04_00_GPS_Time_Tlm_t.csv 2019-04-29T17_58_51-04_00_GPS_Time_Tlm_t.csv	30 2019-04-30T17_38_34-04_00_CAM_Exp_tlm_t.csv 2019-04-30T17_40_19-04_00_GPS_Time_Tlm_t.csv				

Figure 14: STF-1 Experiment Command and Telemetry Calendar

SUMMARY OF ENABLING TECHNOLOGIES

Many of the technologies described here have been indicated previously, but this section will reiterate them so they are in one place and complete.

Virtual machines: The RAP server is a virtual machine running CentOS Linux. Linux provides a capable platform where tools such as cron and at are used for scheduling automated jobs. In addition, bash shell scripts are used extensively to automate the periodic jobs mentioned above. Python scripts are also used for many tasks.

COSMOS: COSMOS was selected as the command and telemetry interface for STF-1. COSMOS was extensively used during development of STF-1. Now that STF-1 is operational, the COSMOS telemetry extractor is used even more and scripts have been created to automatically execute it to create human readable CSV format files of telemetry. In addition, features of the COSMOS command and telemetry server for forwarding telemetry from the MOC to the RAP have been employed. Finally, while not being used extensively yet, the data access and retrieval tool (DART) capabilities of COSMOS have been configured so that database queries for telemetry can be more easily accommodated in the future.

Slack: As mentioned several places, the slack messaging tool is used heavily by the STF-1 team. This includes automatic slack messaging from the RAP server to communicate information such as quick look telemetry/commands and post pass command and telemetry azimuth/elevation graphs. Daily, key graph information is produced on the RAP and shared automatically to the team via slack. In addition, in order to manage the disk space usage on the MOC and RAP machines, a report is automatically generated at midnight each day on the RAP and distributed to the team via slack.

Google Account: The RAP server has a Google account for Google drive sharing. In addition, Google mail is used with this account to receive the WFF scheduling emails with scheduling spreadsheets. Gmail integrations have been used to automatically save off the attachments to the Google drive so that they are available for OIPP runs in order to include schedule information into the OIPP reports.

STK: During the first several weeks of STF-1 contacts, STK was used extensively to visualize the scenarios, discern the separation between the various objects on the ELaNa XIX launch, and understand the inview and contact geometry for WFF antenna to STF-1 contacts.

LESSONS LEARNED

COSMOS was used extensively during STF-1 development and that continues in operations. However, one thing that changed somewhat was the daily contacts with STF-1 with receipt of mission data. In order to not overwhelm the operations personnel, the RAP server was created and as much processing as possible was automated on that server. This includes things like backing up all of the binary command and telemetry logs from the MOC to the RAP daily. It also includes running a daily job that determines when inviews will occur for a day and then scheduling jobs immediately after the inviews. Jobs that execute immediately after inviews then provide immediate feedback status in slack for the STF-1 team and also perform the processing of the binary telemetry into CSV formatted files. Additionally, on a daily basis, the CSV formatted files that are generated are uploaded to the Google drive as well as the original binary telemetry files. Finally, on a daily basis, useful plot data is generated and uploaded to slack.

In summary, it was important to automate all the planning products and post contact product generation, backing up of data, and distribution of data to slack and the Google drive in order to free up STF-1 team personnel for other tasks.

CONCLUSION

This paper has described much of the automation that was put in place to address the needs of operating a low-earth orbiting CubeSat mission. This paper has described the combination of virtualization technologies, ground station technology solutions, collaboration software, custom planning software solutions, and existing ground antenna scheduling solutions that were employed to create an effective and efficient CubeSat operations environment. This environment includes automated report and data generation for planning, operations, post pass analysis, data processing, and data distribution. The end-solution satisfied the operations stakeholders, which include NASA, its industry partner TMC2 Technologies, and four independent professor-student teams at West Virginia University.

REFERENCES

1. Morris, J. et al. (2016): Simulation-to-Flight 1 (STF1): A Mission to Enable CubeSat Software-based Verification and Validation, presented at 54th AIAA Aerospace Sciences Mtg., San Diego, CA, US, Jan. 4–8. Paper 6.2016-1464.

2. Geletko, D.M., Grubb, M.D., Lucas, J.P., Morris, J.R., Spolaor, M., Suder, M.D., Yokum, S.C., and Zemerick, S.A., "NASA Operational Simulator for Small Satellites (NOS^3): The STF-1 CubeSat Case Study," Journal of Small Satellites, Vol. 7, No. 3, December 2018.

3. Grubb, M., Morris, J., Zemerick, S., and Lucas, J. 2016. "NASA Operational Simulator for Small Satellites (NOS3): Tools for Software-based Validation and Verification of Small Satellites", *Proceedings of the AIAA/USU Conference on Small Satellites*, CubeSat Session II: C&DH, https://digitalcommons.usu.edu/smallsat/2016/S2CDH/1/.

4. Grubb, M., Lucas, J., Morris, J., Zemerick, S. 2017. "Utilization of the NASA Operational Simulator for Small Satellites (NOS3) for V&V of STF-1's Semiautonomous On-Orbit Operations", *Proceedings of the AIAA/USU Conference on Small Satellites*, Pre-Conference Workshop Session 1: C&DH, https://digitalcommons.usu.edu/smallsat/2017/all2017/4/.