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Meeting The DoD's Tactical Weather Needs Using CubeSats

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MEETING THE DOD'S TACTICAL WEATHER NEEDS USING CUBESATS

THESIS

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MEETING THE DOD’S TACTICAL WEATHER NEEDS USING CUBESATS

THESIS

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Abstract

This thesis investigates a CubeSat design that uses Commercial-Off-The-Shelf (COTS) components to capture, store, process, and downlink collected terrestrial weather data at resolutions near state-of-the-art. The weather phenomena to be detected and transmitted in a timely manner are cloud formations, wind profiles, ocean currents, sea state, lightning, temperature profiles, and precipitation. It is hypothesized and shown that the proposed design will provide an improvement on the current U.S. tactical weather collection satellites because of the anticipated increased reliability and lowered cost to build and maintain the proposed CubeSat constellation. The methodology employed a multi-phase approach through the collective research of a team of Air Force Institute of Technology (AFIT) master's students to develop an initial satellite design and constellation scheme, with my contributions as the payload lead. This thesis documents the initial satellite design and, through my risk reduction effort to refine the payload, proposes a final payload configuration to meet tactical weather requirements. The final payload includes three types of sensors and is used in 198 identical CubeSats of a LEO Walker constellation. This research has the potential to increase the reliability of weather data collection for the military, while at a low cost to be feasible in the cost constrained environment.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Richard G. Cobb, for his guidance and support throughout the course of this thesis effort. I am thankful for the feedback received from the professors of the Satellite Vehicle Design courses and on my committee, Lt Col Ron Simmons, Dr. Brad Ayres, and Dr. Carl Hartsfield. The insight and experience was certainly appreciated. I grateful for the efforts of my team, and I appreciate the expert advice of the professors in the Physics Department, Dr. Steven Fiorino, Dr. Michael Hawks, and Lt Col Robert Wacker. I would also like to thank my husband for his patience and support throughout this program.

Shayna J McKenney

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List of Acronyms

ABI	Advanced Baseline Imager
ADCS	Attitude Determination and Control Subsystem
AFIT	Air Force Institute of Technology
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AOV	Angle of View
ATMS	Advanced Technology Microwave Sounder
CBO	Congressional Budget Office
C&DH	Command and Data Handling
COTS	Commercial-Off-The-Shelf
CrIS	Cross-Track Infrared Sounder
CYGNSS	Cyclone Global Navigation Satellite System
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
EPS	Electrical Power Subsystem
FASTRAC	Formation Autonomy Spacecraft with Thrust, Relnav, Attitude and Crosslink
FORTE	Fast On-orbit Rapid Recording of Transient Events
FOV	Field of View
GLM	Geostationary Lightning Mapper
GNSS	Global Navigation Satellite Systems

GOES	Geostationary Operational Environmental Satellite
GPI	GOES Precipitation Index
GPS	Global Positioning System
GSD	Ground Sample Distance
IR	Infrared
JPSS	Joint Polar-orbiting Satellite System
LEO	Low Earth Orbit
LLS	Lightning Location System
LWIR	Long Wave Infrared
MC3	Mobile CubeSat Command & Control
MicroMAS	Micro-sized Microwave Atmospheric Satellite
MiRaTA	Microwave Radiometer Technology Acceleration
MOP	Measure of Performance
MW	Microwave
MWIR	Mid Wave Infrared
NASA	National Aeronautics and Space Administration
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
OLS	Operational Linescan System
OSCAR	Ocean Surface Current Analyses Real-time
OTD	Optical Transient Detector
POES	Polar-Orbiting Operational Environmental Satellite

RAOV	Restricted Angle of View
RAX	Radio Aurora Explorer
SENSE	Space Environmental NanoSat Experiment
SMC	Space and Missile Center
SNPP	Suomi National Polar-orbiting Partnership
SSMIS	Special Sensor Microwave Imager and Sounder
STK	Systems Tool Kit
STTR	Small Business Technology Transfer
TMI	TRMM Microwave Imager
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TT&C	Telemetry, Tracking and Command
UK-DMC	United Kingdom – Disaster Monitoring Constellation
VHF	Very-High Frequency
VIIRS	Visible Infrared Imaging Radiometer Suite
WSF	Weather Satellite Follow-On

MEETING THE DOD’S TACTICAL WEATHER NEEDS USING CUBESATS

I. Introduction

1.1 General Issue

The United States military has depended on the Defense Meteorological Satellite Program (DMSP) as its primary collector of tactical weather data for over 50 years, since 1962 [1]. Weather is a significant factor in combat operations planning, as it affects the effective movement of military assets, as well as the communications. Timely, tactical weather data allows commanders to make critical decisions when they typically have little to no control over the outcome of adverse weather. Starting in September, 1979, through August, 1980, each of the four operational DMSP satellites failed to function one after the other, leaving a gap in the meteorological coverage for the nation. The military was forced to rely on the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) civil satellites, among other weather collection programs, to fill the data gap until three replacement DMSP satellites could be launched in 1983 through 1987 [2]. The Air Force claimed that DMSP was “indispensable” to the military for weather data collection, but the reliance on NOAA and NASA satellite during the capabilities gap proved otherwise. The DoD and NOAA continued to work together to provide weather data for civil and military use, even using a common satellite bus on two separate programs. As a way to reduce cost due to redundancy in military and civil weather satellite capabilities, a joint Department of Defense (DoD) and NOAA/NASA program was formed in 1995, called National Polar-Orbiting Operational Environmental Satellite System (NPOESS). Yet, in 2010, the

NPOESS program was cancelled due to severe cost overruns and delays typical of complex satellite designs. A restructured concept relies on the DoD DMSP to monitor the AM orbit independently from NOAA/NASA satellites monitoring the PM orbit[1], yet all six DMSP satellites are operating past their design life of five years [4]. The U.S. military, once again, faces the challenge of collecting tactical weather information with a satellite constellation on the brink of failure.

The Congressional Budget Office (CBO) released a series of working papers outlining options for replacing DMSP, where they considered the alternative approach of "fielding single instruments on several small satellites instead of several instruments on a single satellite" [5]. The expected replacement to DMSP is the Weather Satellite Follow-On (WSF), which will incorporate this idea of disaggregated system-of-systems [6]. The microsatellite constellation design of WSF is a step in the right direction for combating the vulnerabilities that exist in the current weather satellites. These vulnerabilities include poor manufacturing timeliness, high costs that risk program cancellation during budget cuts, and loss of weather coverage in the event of a satellite failure. Many weather satellites are designed from a complex list of various capabilities, leading to extremely unique designs that require expensive and time-consuming research to successfully build and launch [7]. The outcome is fewer satellites due to cost, a constellation at higher risk of failure from under-tested designs, and systems that are difficult to replace due to the time needed to manufacture. This research offers a possible

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[1] AM and PM orbits refer to sun-synchronous polar orbiting satellites, which cross the same location on Earth at the same local time every day for consistent lighting. AM satellites ascend across the equator near North America around sunrise and PM satellites ascend around sunset [3].

CubeSat[2] design to be incorporated in a nanosatellite constellation scheme to monitor and report terrestrial weather. CubeSats utilize off-the-shelf components, which are inexpensive and fast to produce replacement satellites. With a focused set of mission requirements, CubeSat constellations can be designed, built, tested, and launched for a small investment. Thus, it is hypothesized that this design can meet the terrestrial weather data collection needs of the U.S. military quickly and inexpensively.

1.2 Problem Statement

This thesis investigates a CubeSat design that uses Commercial-Off-The-Shelf (COTS) sensors and systems to capture, store, process, and downlink collected terrestrial weather data at resolutions near state-of-the-art. The weather phenomena to be detected and transmitted in a timely manner are cloud formations, wind profiles, ocean currents, sea state[3], lightning, temperature profiles, and precipitation. The proposed design will look at providing an improvement on the current U.S. tactical weather collection satellites because of the anticipated increased reliability, lowered program cost, and timeliness to build and maintain the proposed CubeSat constellation.

1.3 Methodology

The methodology used to create the proposed CubeSat design employed a multi-phase approach through the collective research of a team of Air Force Institute of Technology (AFIT) master's students. The team was tasked to develop an initial satellite

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[2] CubeSats are a class of miniaturized satellites defined by their modular volume and mass. The dimensions are 10x10x10 cm, with a mass of 1.33 kg for a 1U satellite [38]. This thesis considered an initial satellite design between 1U and 27U.

[3] Sea state refers to ocean surface roughness, which is a function of average wave height and frequency.

and constellation scheme during the master's courses, ASYS 531 and ASYS 631[4]. The effort included refinement of the given mission requirements [8], high-level trade-offs to produce subsystem level budgets and constellation design, and a component level trade study for an initial satellite design. The team developed a CubeSat, called the WeatherSat, through individual research that was vetted during weekly team meetings with the course professors. At the end of the course series, the initial WeatherSat design still had payload risks that were then addressed in this research.

The first phase, which was executed in the ASYS 531 course, explored high-level trade-offs of the mission requirements to further define subsystem requirements. These trade-offs included prioritizing mission and system requirements and constraints on performance, such as power, mass, and volume budgets for a 27U CubeSat.

The second phase developed a sensor suite and bus design through subsystem considerations and a component level trade study, which was performed in the ASYS 631 course. The preliminary satellite design, constellation scheme, and program cost was completed in this phase.

The final stage examines the WeatherSat's risks concerning the payload. There were some design choices that proved to be suboptimal once the whole design was established. These risks are analyzed further in the last phase and leads to the final WeatherSat constellation design and recommendations for further research.

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[4] ASYS 531 and ASYS 631 are course codes for the Space Mission Analysis and System Design course and the Spacecraft Systems Engineering course, respectively.

1.4 Assumptions/Limitations

A majority of the research done on the WeatherSat was through a team effort in the courses ASYS 531 and ASYS 631. The team was given one page of mission requirements from which to make design decisions [8]. The workload was divided into subsystems, where I was the lead for the payload development. Many of the constraints given to the team were derived from the desired performance of the CubeSat, yet the rest of the mission requirements listed on the one-pager were created to help narrow the scope of the research into a ten-week course. Overall, the mission requirements and research conducted by team members are assumed to be valid and reasonable. Also, any COTS devices researched are considered to have accurate specifications, deliverable, available with no lead time, and can integrate into the satellite system.

Limitations of this research concern the availability of information on the component costs and performance with the candidate sensors as well as current weather satellite sensor specifications. When limited by a lack of information, the team gave an educated guess and moved forward with that assumption.

The mission requirements are listed in priority order, shown in Table 1. The mission requirements directly shaping the design of the payload sensor suite, which is the focus of this thesis, are placed above the remainder of the mission requirements.

Table 1 Mission Requirements ASYS 531 Mission Goals [8]

Name	Description	Priority
Requirements for Payload Design		
Cloud Detection	The system shall detect and locate clouds to within 10 km	1
Temperature Mapping	The system shall detect and map temperatures to within 10 km	2
Precipitation	The system shall detect and locate precipitation to within 10 km	3
Wind/Ocean Currents	The system shall detect and locate wind/ocean currents to within 10 km	6
Sea State	The system shall detect and locate sea state to within 10 km	7
Lightning Detection	The system shall detect and locate lightning to within 10 km	8
Resolution	The system shall be comparable to state of the art systems	10
Form Factor	The satellite shall conform to standard "U" form factor[5]	12
Remainder of the Mission Requirements		
Rapid Download	They system shall be capable of downloading all data within 30 minutes of detection	4
World Wide Coverage	The system shall have < 30 minutes revisit rate at any location in the world (threshold), or continuous coverage (objective)	5
Data Storage	They system shall be capable of storing all collected data between downlinks	9
Ground Station	The system shall use the MC3 University Network	11
Satellite Cost	The satellite bus (not including payload or propulsion) shall cost less than $500K per satellite	13
Launch Cost	The launch system shall cost less than $1M per satellite	14

1.5 Implications

The main outcome of the thesis is a proposed design for a CubeSat to collect and transmit weather data, and leads to the ground work for an executable constellation scheme. This research has the potential to significantly improve the military utility of the collected data, as timelines to downlink and disseminate data on mission critical weather needs is minimized. The Navy has already expressed interest in the cost effective possibilities of CubeSats for maritime weather data collection [9].

A less obvious contribution of the final design is the gained understanding of what information can be gathered through such a small investment, even outside of the

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[5] There is no limit of how many units the CubeSat design can be, but the team chose "U" form factor based on existing deployment systems. This limited the choices to 1U, 2U, 3U, 6U, 12U, and 27U.

weather mission. The same visible sensor that observes cloud coverage and lightning can also identify contrails and the detonation of bombs. Also, the modularized sensor suite can be utilized on other satellite platforms as an independent weather detection unit, providing unique and instant information for the immediate use of that satellite.

1.6 Preview

This thesis documents the systems engineering effort of a team of AFIT master's students to develop an initial CubeSat constellation, which collects weather data for the planning of tactical military movements, and provides design refinement for a proposed final CubeSat design that meets mission requirements. Chapter I outlined the necessity of this research and the impact it can have for its user. Chapter II provides a literature review of current weather satellite capabilities and what sensors are used in weather data collection. The methodology, in Chapter III, explains the process and equations used to make design decisions leading to the preliminary and final satellite designs. Chapter IV contains the team results from analyzing mission requirements, my results from sensor considerations and component level analysis of the payload suite, a summary of the initial satellite design and constellation scheme with cost estimation, my discussion of design refinement for the payload sensor suite, and a comparison of my proposed final WeatherSat payload design to meet the mission requirements. Finally, Chapter V makes recommendations for future research and concludes the impact of the final WeatherSat design.

II. Literature Review

2.1 Chapter Overview

The purpose of this chapter is to introduce the methods by which the weather phenomena are typically measured, show the resolution of sensors found on current, state-of-the-art satellites that perform weather detection, and present nanosatellite research achievements related to this weather collection mission.

2.2 Methods of Measuring Weather Phenomena

The seven weather phenomena that the CubeSat is required to detect and measure are: lightning, cloud formations, wind profiles, ocean currents, sea state, temperature profiles, and precipitation. Each phenomenon can be measured multiple ways and therefore, with a variety of sensors. In this section, the array of options is presented and serves as the starting point of the payload sensor suite considerations for the proposed WeatherSat design. Each method of measurement is examined to determine what sensors can be supported by a CubeSat platform and the best suite of sensors to cover the desired weather monitoring. A majority of the research in this section was accomplished with the textbook on remote sensing [10], so any additional citations will be cited appropriately.

2.2.1 Lightning Detection

Identifying variability in lightning provides information concerning properties of clouds and thunderstorm intensity. If sensing lightning is limited to ground-based measurements, one misses indicators found over the oceans and those that cannot be found in only detecting cloud-to-ground lightning. The first satellite to sense lightning, day or night, was the Optical Transient Detector (OTD) in 1995. Taking readings in the visible band, OTD found that Central Africa had the highest density of lightning, along with other tropical regions across the world.

Another method of detecting lightning is sensing the electromagnetic radio frequency energy that lightning produces. The photodiode detector, on Fast On-orbit Rapid Recording of Transient Events (FORTE), is a Very-High Frequency (VHF) instrument that senses each phase of the lightning flash. Typically, this method produces poor spatial resolution, 100s of kilometers. But FORTE simultaneously makes observations using its Lightning Location System (LLS) imager to improve the spatial resolution to 10 km [11], the same resolution as OTD.

2.2.2 Detection of Cloud Formations

Clouds play an instrumental role in the radiation balance of Earth’s atmosphere, as they covers about two-thirds of Earth’s surface. The properties, structure, altitude of clouds provide lots of information about the weather in that region. In fact, the GOES Precipitation Index (GPI) sensor uses IR-based hurricane cloud signatures to predict the rain rate of each part of the hurricane system.

Cloud formations are typically detected with visible images, as they contrast nicely with land and oceans. With a visible camera, one can see how thick or hazy thin a cloud is and make predictions about its height and precipitation capability. Also, tall clouds cast shadows. This is a characteristic of the Cumulonimbus clouds, which produce thunderstorms.

The temperature of cloud tops tell us about their altitude. Warmer clouds will be lower to Earth’s surface and colder clouds are usually higher in altitude. The use of IR sensors, mainly in the mid wave and long wave range, captures this information and helps in weather prediction.

Microwave radars, measuring in the millimeter-wavelength either actively or passively, can also be used in providing properties of the clouds, such as precipitation rates, liquid water content, and concentration. The first satellite to use microwave radar as a way to categorize clouds and weather was CloudSat. Its measurements showed red/orange for high cloud water content to blue for icy clouds.   Figure 1 shows the profile CloudSat captured of the Tropical Storm Ernesto, where the cloud cover may lead one to conclude that the storm is symmetrical, yet the right side of the storm has a much heavier rainfall.

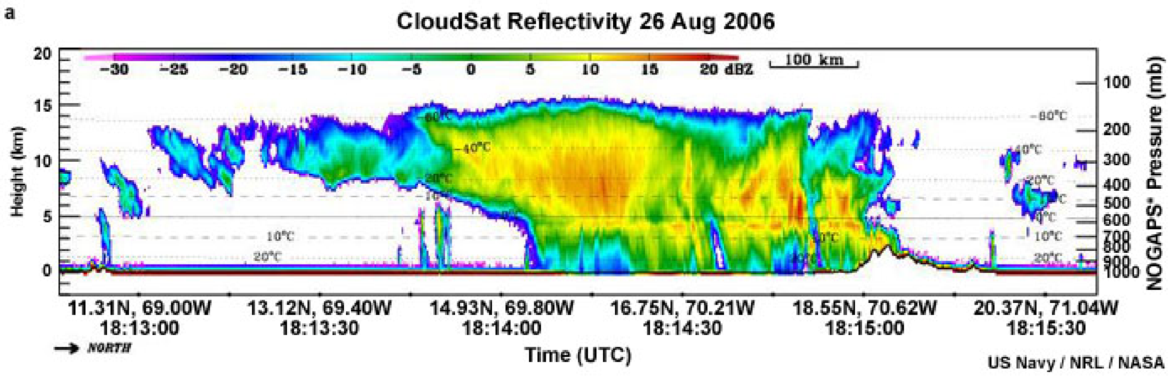


Figure 1 CloudSat Profile of Tropical Storm Ernesto [10]

Cloud properties are closely linked to other weather phenomena discussed. It is important to capture as many properties as possible to have the best resolution for weather prediction. Using all methods, visible, IR and microwave radar, will be a part of the considerations for payload sensors for this research.

2.2.3 Temperature Profiling

Infrared sensors are able to measure temperature profiles throughout the atmosphere due to the variation in radiation absorption at different altitudes. In order to have an accurate prediction of temperature based on observed radiance, the composition of gases has to be known and be uniform. Typically, sounders are hyperspectral, detecting small changes in readings to identify specific temperatures. The Atmospheric Infrared Sounder (AIRS), flown on Aqua, has a vertical resolution of 2 km.

Another method of profiling temperatures is through radio occultation, depicted in Figure 2. This technique uses temperature and moisture gradients in the atmosphere to refract GPS signals, arriving over the horizon, towards the receiving satellite. The amount of refraction reveals the temperature profile. The COSMIC satellite utilizes GPS radio occultation and has 100 m resolution in lower troposphere [12].

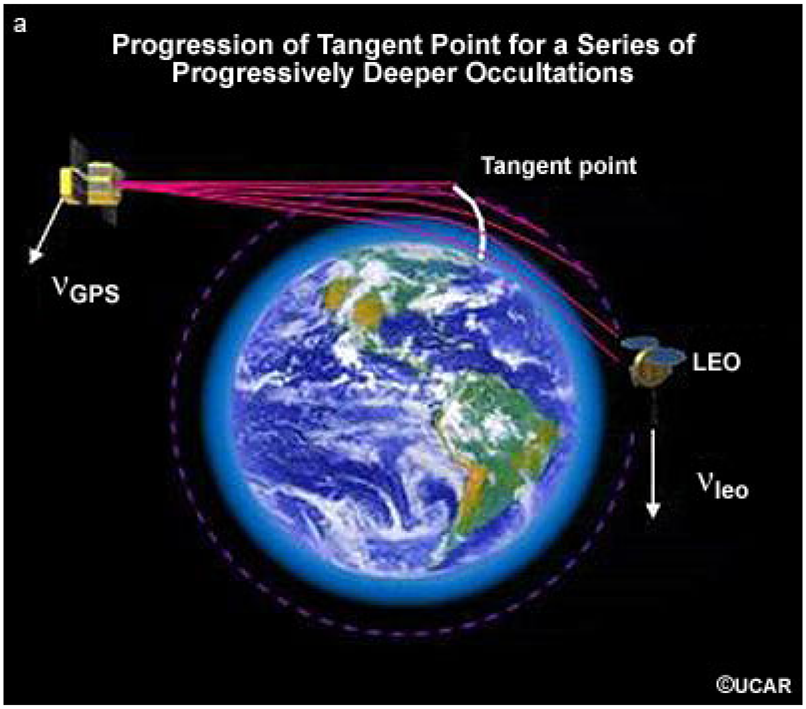
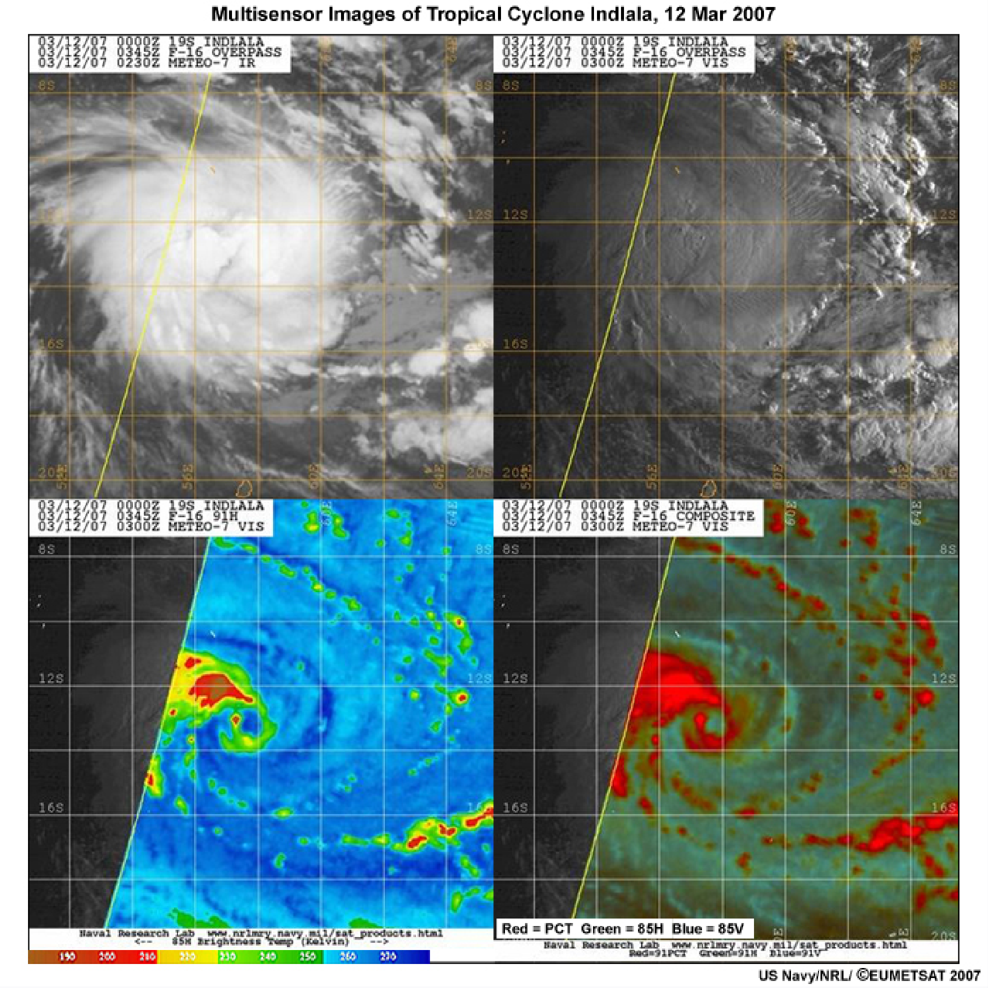


Figure 2 Radio Occultation [10]

2.2.4 Measurement of Precipitation

As mentioned in detecting cloud formations, some instruments like GPI use IR signatures of clouds to estimate precipitation rates. The colder the cloud usually indicates a taller formation, which is known for higher precipitation rates. The weakness of IR measurements is that their lower-resolution tends to misidentify non-precipitating, high-altitude, cold cirrus clouds with cloud formations that do precipitate. Also, the IR measurements don't identify the lower-altitude warm rain clouds. The overall estimates tend to underestimate the beginning of precipitation dominated by warm rain clouds and overestimate the ending of a precipitation cycle with cold cirrus clouds.

Microwave sensors are an improvement to measuring precipitation to the IR sensors. Microwave sensors can directly detect precipitation by measuring the scattering and emission signatures of water and ice. The microwave channels are able to see through the clouds to the surface of the Earth, but are affected by the properties of precipitation. As seen in Figure 3, IR images of some cyclones may not show the eye of the storm, which is critical information when predicting the intensity and path. The microwave measurements always clearly show the eye and detailed information about the structure of the cyclone. Emission measurements to measure rain are typically used over the ocean, which has a low and uniform emissivity background. This is the primary technique of DMSP SSMIS sensor. Over land, scattering in the 85 GHz band is common to use because land has high variations in emissivity. Also, ice scatters at this band, making it ideal for snow detection. This technique is used by the Advanced Microwave Sounding Unit (AMSU), used by many Earth observing satellites. There are weaknesses to the method of microwave sensing though. Surface snow and ice, along with areas highly concentrated with clouds, can skew measurements in precipitation.



US Navy/NRL/ ©EUMETSAT 2007

Figure 3 Infrared Vs. Microwave Remote Sensing [10]

An accidental method of measuring rain rates came about from scatterometry instruments measuring sea states and wind profiles, depicted in Figure 4. The attenuation caused by rainfall affected accurate readings of backscatter from ocean surface roughness. Further, it was found that at high rain rates, above 5 mm/hour, the rain drops were larger and oblate in shape. This difference in shape during heavy rainfall produces a radar signal that has more horizontal polarization than vertical polarization, and can reliably measure rain rate. Scatterometry measurements are comparable with the common method of microwave sensing, as noted when the SeaWinds scatterometer estimates were compared to the microwave instrument measurements flown on the Tropical Rainfall Measuring Mission (TRMM) satellite, called the TRMM Microwave Imager (TMI).

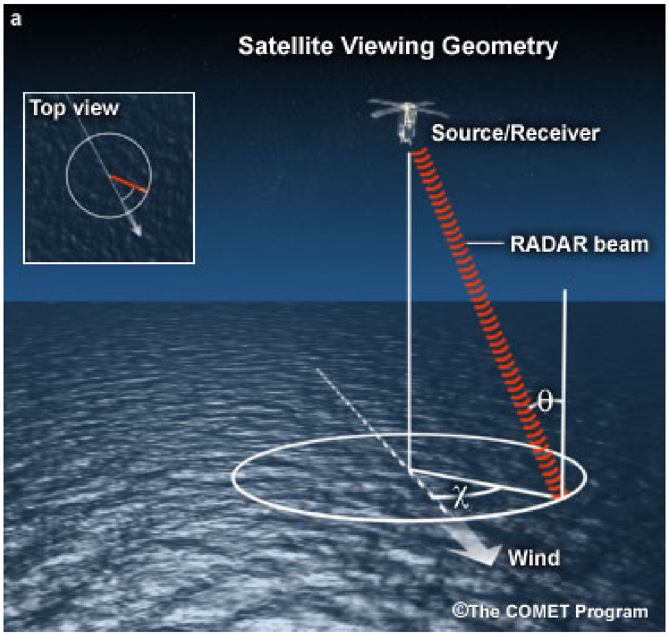


Figure 4 Scatterometry Observation Concept [10]

2.2.5 Measurements of Sea State

The primary method of measuring sea state is through scatterometry with microwave sensors. This technique can detect small variations in ocean surface roughness, from breaking waves to foam. Many of the satellites collecting sea state information are using the data to retrieve wind velocity vectors across the ocean surface to predict weather systems heading towards land. The SeaWinds scatterometer of the QuikSCAT satellite is able to provide spatial resolution of wind measurements at 25 km.

It sends microwave pulses down to the surface and measures the backscatter, then backs out wind velocity and direction. A weakness of this method is rain interference that creates additional backscatter.

A second instrument used in measuring sea state, specifically sea height, is the altimeter [13]. The altimeters use radar signals to measure the distance from the satellite to the ocean surface. The altimeter distance measurements are combined with atmospheric disturbance measurements by a microwave radiometer and positioning information from GPS satellites and ground laser ranging stations to determine sea height from the reference geoid[6], as seen in Figure 5. Currently, the satellite Jason-2 provides altimeter measurements and QuikSCAT obtains scatterometry information for the OSCAR project [14].

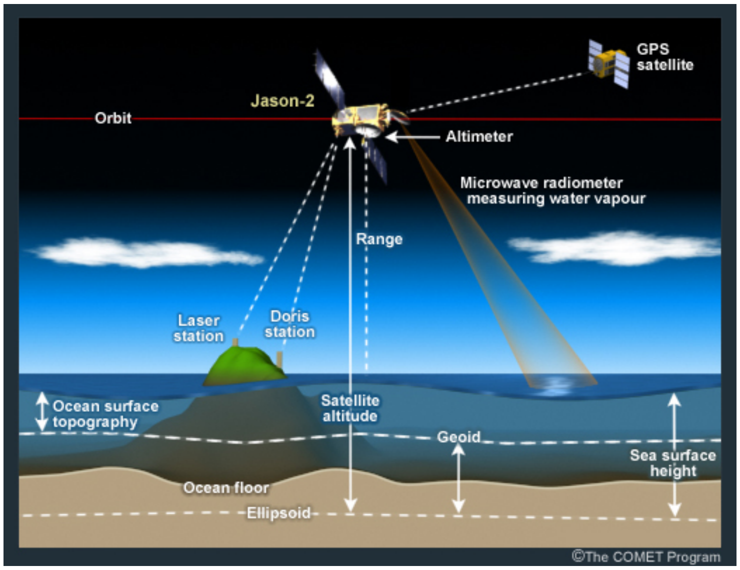


Figure 5 Jason-2 Satellite Altimeter [13]

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[6] The geoid is the “average global sea level” [13].

2.2.6 Wind Profiling

Wind profiles cannot be directly measured from space, but they can be estimated through observations of sea state and temperature profiles. Satellites use microwave scatterometry to measure the roughness of the ocean and extrapolate wind vectors at the surface. This is accomplished through calibrating the bistatic radar cross section measurements with empirical wind-wave models, using reflection geometry on the scattered signal to determine the ocean wave slopes, then deriving the surface wind vectors from an empirical function. The results of this method have been validated with the United Kingdom – Disaster Monitoring Constellation (UK-DMC) satellite against in situ measurements of ocean buoys, provided by the National Data Buoy Center (NDBC) [15].

Scatterometry covers wind calculations at the ocean's surface, but it cannot provide wind profiles throughout the remaining atmosphere. This information also cannot be measured directly, but it can be estimated through temperature profile data. A temperature gradient causes differences in air pressure that lead to wind as the atmospheric pressure attempts to equalize. Typically, the greater temperature gradient results in faster winds. Temperature profiles can be measured through IR sounders and radio occultation.

One last method to estimate wind vectors is simply observing the movement of cloud formations. This can be done with a visible camera using a series of time stamped images. Yet with any of the methods, wind data must be derived from other measurements.

2.2.7 Ocean Current Detection

In addition to wind profiles, ocean currents also cannot be measured directly with a satellite instrument. NOAA's project, Ocean Surface Current Analyses Real-time (OSCAR), utilizes multiple satellites and their sensors to estimate ocean currents. The sensors collect data on sea surface temperature with IR sensors, wind calculations through radio scatterometry, and sea height using active radar altimeters, and combine this information into a model to estimate ocean currents [16]. Radio scatterometry is the same as what SeaWinds performs, but it is done passively through reflections of other satellite signals. One such signal often used is Global Navigation Satellite System (GNSS), as shown in Figure 6.

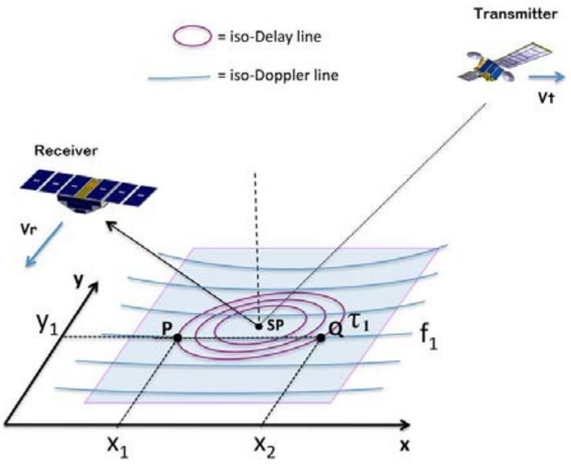

Figure 6 Geometry of a GNSS-R Measurement of the Delay Doppler Map [17]

Wind is the main influence in surface currents, along with Coriolis forces and interactions with land masses. Deep water currents are mainly generated by variations in temperature and salinity. Yet no matter the catalyst for the current, the currents are comprised of large masses of water with similar temperature [18]. Therefore, reasonable data can be collected with IR sensors to determine ocean currents.

Table 2 provides a summary of the possible sensors and methods that can be used to detect and measure the weather phenomena focused on in this thesis. Although each instrument can detect or measure the weather phenomenon of interest, not all of the sensors can measure the full range of the characteristics that is desired. Support sensors, which help predict a weather phenomenon but cannot be the sole instrument, are indicated by "+". A discussion of the sensor that provides the best data on each weather phenomenon is covered in Chapter IV.

Table 2 Summary of Sensor Options derived from Literature Review

Weather Phenomena	**Sensor/Method Options**						
	Lightning	Cloud Formation	Temperature Mapping	Precipitation	Sea State	Wind Profiles	Ocean Currents
VHF instrument	✓						
Visible camera	✓	✓				✓	
MWIR radiometer		✓	✓				
LWIR radiometer		✓	✓	✓		✓	✓
LWIR sounder			✓				
MW radiometer		+	✓	✓	✓	✓	
GPS occultation			✓				
GPS scatterometry				✓	✓	✓	+
Altimeter					✓		+

2.3 Current U.S. Weather Satellites

Weather detection is a priority in all countries. Governments in the U.S., Europe, Russia, China, Japan, and others invest in weather satellite programs, and utilize the data collected for military purposes as well as other facets of their lifestyle. Their satellites are diversified into the continuous observations of the geostationary satellites and the intermittent yet high resolution collection of the polar orbiting satellites. A reliable replacement of current weather satellites would need to provide quality, continuous global coverage.

To define the standard of quality required of a nanosatellite to be a feasible option, the current capabilities of state-of-the-art satellites is explored, specifically of the seven weather phenomena requested. The following paragraphs will outline the capabilities of the United States' polar-orbiting satellites: 1) the DoD Defense Meteorological Satellite Program (DMSP) F19, 2) the National Oceanic and Atmospheric Administration (NOAA) Joint Polar-orbiting Satellite System (JPSS), and 3) the latest NOAA Geostationary Operational Environmental Satellite (GOES).

DMSP has been in production for over 50 years, and has provided the military with excellent weather detection through two primary sensors, the Operational Linescan System (OLS) and the Special Sensor Microwave Imager and Sounder (SSMIS). Through visible and infrared imaging, the OLS can detect clouds and measure surface temperatures on land and sea [19]. The visible telescope operates in the 0.4-1.1 μm band, and the infrared sensor is sensitive to the 10-13.4 μm band. The resolution of the OLS is between 0.55 and 2.7 km [20]. The SSMIS is an outstanding asset of DMSP, as it can measure temperature profiles, sea surface wind, precipitation, and also surface temperature. This polarized passive microwave radiometer operates between 19 and 183 GHz, and has a spatial resolution of 13-75 km [21].

JPSS-1 is the second of three polar-orbiting weather satellites to replace the aging NOAA Polar-Orbiting Operational Environmental Satellite (POES) constellation, launched in 2000 through 2009 [22]. The first satellite, Suomi National Polar-Orbiting Partnership (SNPP), and the future JPSS satellites have leveraged the technology of heritage instruments from NOAA POES and Department of Defense (DoD) DMSP. Two of the instruments are used for detection of cloud formations, precipitation, and temperature profiling, which are the Advanced Technology Microwave Sounder (ATMS) and Visible Infrared Imaging Radiometer Suite (VIIRS) [23]. ATMS has 22 spectral bands from 23-183 GHz and has a spatial resolution between 15.8 and 74.8 km [24]. VIIRS also has 22 spectral bands, ranging from 0.412-12 μm. It has excellent resolution at 0.75 km [25].

NOAA's GOES-R is the first of four geostationary satellites to replace the operational legacy spacecraft, which were launched between 2006 and 2010 and are at their end-of-life [26]. The next generation of GOES boasts of major advances in geostationary observations, with improvements in the Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM) sensors and more accurate monitoring of space weather [27]. The ABI has 16 spectral bands in the visible, near-infrared (IR), and IR range for cloud/fog detection among other land properties. The spatial resolution is 0.5 km to 2 km, which is four times better than the legacy sensor [28]. The GOES-R also houses the GLM for lightning detection. The GLM is a near-IR sensor, which can detect lightning to within 14 km [29]. These two sensors will allow GOES-R to track and monitor the development of severe weather, such as hurricanes, after its launch this year [27].

From the performance of DMSP F19, JPSS-1, and GOES-R, the standard of resolution quality for each of the weather phenomena is captured in Table 3. A successful nanosatellite sensor suite will be able to capture the weather phenomena near the values listed to be considered a feasible alternative to the current weather satellites.

Table 3 Standard Resolution Quality derived from State-of-the-Art Weather Satellites

Weather Phenomena	Standard of Resolution Quality	References
Lightning	14 km	GOES-R GLM [29]
Cloud Formations	~ 0.6 km* (range 0.5 - 0.75 km)	Average of DMSP OLS [20], JPSS-1 VIIRS [25], and GOES-R ABI [28] capabilities
Land Temperature	~ 2.4 km* (range 2 - 2.7 km)	Average of DMSP OLS [20] and GOES-R ABI [28] capabilities
Atmospheric Temperature and Wind Profiles	39.5 km	Average resolution of DSMP SSMIS over 19-55 GHz [21]
Precipitation	13.5 km	Average resolution of DSMP SSMIS over 92-150 GHz [21]
Sea State and Ocean Currents	48 km	Average resolution of DSMP SSMIS over 19-37 GHz [21]

*Average value is reasonable for these comparable sensors.

2.4 Nanosatellite Missions

A couple of nanosatellite programs seeking to perform comparably to current satellites are the Micro-sized Microwave Atmospheric Satellite (MicroMAS) and the Microwave Radiometer Technology Acceleration (MiRaTA), by Massachusetts Institute of Technology [30]. MiRaTA, and its successor MicroMAS, are passive microwave radiometers designed to detect severe weather, such as thunderstorms and hurricanes, through temperature mapping and precipitation measurements. The radiometers do not emit the microwave signal themselves, but receive information about objects of interest through black body radiation and reflected solar radiation [31]. At an orbit of 400 km, MiRaTA has a goal of 10 km resolution with measurements in the 55, 183, and 207 GHz range. The resolution of 10 km is well below the current standard of about 13.5 km for precipitation measurements and around 39.5 km for temperature mapping.

Other weather related nanosatellite successes are the space environment measurement achievements of Space Environmental NanoSat Experiment (SENSE) and Radio Aurora Explorer 2 (RAX-2). SENSE was developed by the Space and Missile Center (SMC) to collect data on the ionosphere that may adversely affect signals from Global Positioning System (GPS) satellites to military users. Over the 16 months on-orbit, SENSE demonstrated the reliability of many COTS payload and bus components, all while meeting military standards of data encryption and radiation tolerance [32]. The University of Michigan and Stanford Research Institute International collaborated efforts to develop RAX-2, which is designed to study ionospheric disturbances through the use of bistatic radar. In 1.5 years of operation, RAX-2 performed over 30 experiments and provided measurements comparable to standard satellites [33].

The non-weather mission accomplishment of Formation Autonomy Spacecraft with Thrust, Relnav, Attitude and Crosslink (FASTRAC), by the University of Texas at Austin, demonstrated crosslink communications. FASTRAC was able to crosslink thousands of messages over an amateur ultra-high frequency band for the 1.5 years it was operational [34]. Crosslinks ensure timely data downlinking without an abundance of ground stations that opens many space missions to constellations of small satellites.

State-of-the-art weather satellites typically collect more terrestrial data than the seven weather phenomena this thesis examines, and most of the satellites also collect space environment data. Yet, the achievements of some nanosatellite programs, SENSE by the U.S. Space and Missile Center and RAX by the University of Michigan, show the feasibility of using nanosatellites to rival current satellite capabilities, specifically in the measurement of space environment. Similarly, this research takes a set of weather satellite capabilities with a tactical military application and studies whether nanosatellites are a viable replacement.

2.5 Summary

A few U.S. weather satellites were introduced as a standard of performance of current, state-of-the-art satellites. Some of the capabilities have been matched by nanosatellite projects and more of these satellite capabilities are being demonstrated as feasible alternatives to the costly programs funded today. It is not implausible that a CubeSat constellation, designed to detect cloud formations, lightning, precipitation, temperature and wind profiles, sea state, and ocean currents, is also capable of matching current performance levels. The introduction to current weather detection methods is the start to the payload sensor suite considerations to narrow down the sensors needed for the CubeSat mission.

III. Methodology

3.1 Chapter Overview

The purpose of this chapter is to document the multi-phase methodology used to produce the proposed CubeSat design for the weather mission. The first phase explores high-level trade-offs between mission requirements for the subsystems, deciding priority and budgets for power, mass, and volume constraints. The second phase develops a possible sensor suite and bus design through component level trade studies. The overall design includes constellation scheme and cost summaries, and is used to compare the WeatherSat constellation to state-of-the-art weather satellite programs. The final phase, which is also accomplished in this thesis, examines the payload sensor suite design risks and recommends future research to further reduce payload risk and to optimize the constellation scheme for lower cost and improved reliability.

3.2 Phase 1

The first phase of determining an initial design was to perform high-level trade-offs of mission requirements amongst the subsystems of the CubeSat. This phase was accomplished through a team of students in the Air Force Institute of Technology (AFIT) course, ASYS 531: Space Mission Analysis and System Design. The team analyzed mission requirements by prioritizing them based on what would be most valuable to the user. The top priorities reflect tactical weather mission needs, which are deemed essential for a successful WeatherSat mission. The mission requirements that were given lower priority, if not met, could still result in a successful mission, but would not be the desired solution.

Next, the system functional and non-functional requirements were developed to meet the mission requirements. Through the Enterprise Architect tool, the team organized the system functional and non-functional requirements that are derived from the mission requirements. The team kept careful track of the traceability from mission requirements down through derived requirements with a Traceability Matrix. Then these lower level requirements were allocated to the appropriate subsystems along with the technical budget allocations. The team used reference [35], which had statistical allocations of mass and power for Low Earth Orbit (LEO) satellites. Although the satellites used in the textbook are, at least, an order of magnitude larger in scale, this data provided a start for WeatherSat allocation decisions. Adjustments for WeatherSat allocations were made due to identified differences in the mission, size of satellite, and types of subsystems in the statistical data versus the WeatherSat. Also, other adjustments were made as new component information was available. These changes are discussed in Chapter IV.

3.3 Phase 2

The second phase of the WeatherSat design process was accomplished by the team in the AFIT course, ASYS 631: Spacecraft Systems Engineering, where the preliminary satellite design, constellation scheme, and program cost estimation was completed. The sensor suite and bus design, and constellation scheme were developed through subsystem considerations and a component level trade study. The team conducted individual research focused on their respective subsystem or mission area and presented their conclusions and findings during a weekly team meeting. Original technical budgets were adjusted by team consensus as new information revealed infeasibility in current budget constraints. Also, major design decisions, such as adding the capability of crosslinking to meet downlink requirement of 30 minutes, was vetted with the course professors for professional feedback. The methodology for the payload sensor considerations, technical budgets, and component level trade study are explained in sections 3.3.1 through 3.3.3, with a discussion of the program cost estimation method in section 3.3.4.

3.3.1 Payload Sensor Considerations

Through the literature review in Chapter II, many methods of collecting weather data was discovered. The possible options for sensors need to be narrowed down to those which can physically fit on a CubeSat and operate under the limited power available, as well as those sensors which provide the best resolution for the weather phenomena of interest at the lowest risk to mission success. The success criterion for a single sensor to be considered supportable on a CubeSat was 50% of the allotted technical budget for the entire payload sensor suite. The 50% limitation was selected because there may be up to 9 components, which are expected to be comparable in size as miniaturized sensors. The sensors won’t be rejected if they fall within the following values: 1) 5.4 kg mass, 2) 2.7 U volume, and 3) 6 W of power consumption. Other factors that led to rejection of a sensor option is if the sensor cannot measure the entire range of characteristics of the weather phenomena with desired accuracy or the complexity of utilizing the sensor adds risk for the payload design.

3.3.2 Payload Budgets and Equations

Besides the mass, volume, and power constraints, the team had to allocate the other derived requirements responsibilities to the subsystem. There were requirements that affected more than one subsystem, such as the geolocation and data rate requirements. For each shared requirement, the team researched the range of acceptable performance for each subsystem and selected an achievable constraint to continue the design process.

The constraints now set for each subsystem allowed each team member to decide success criteria for their component level trade studies. For the payload, the budgets for mass, volume, power, and data rate were divided between the four sensors based on the average values found in research of component specifications. Discussion of the shared requirements for payload and the sensor budget results are in section 4.3.2.

The component specifications often are not in the form needed to directly compare against requirements. Figure 7 and the Equations (1.1) through (1.9) help to convert the limited information into key values, concerning constraints needed for the payload sensor suite design. These key values include: the ground sample distance (GSD) and the focal length needed to achieve that GSD, the resulting data rate after duty cycling, and the power consumption during operational use. Also, the sensors need to be checked to see if they are diffraction limited for the resolution desired.

Figure 7 depicts a one dimensional geometry of a field of view (FOV) captured by a sensor. Equation (1.1) shows that the focal length and sensor size is proportional to the FOV and working distance. The GSD is the portion of the FOV as captured by a single pixel of the sensor, as seen in Equation (1.2). With a set GSD value from the resolution requirement and a small range of altitudes being considered for the working distance (600-1000 km[7]), the components considered in the component trades study had to fit the remaining range for the focal length and pixel size.

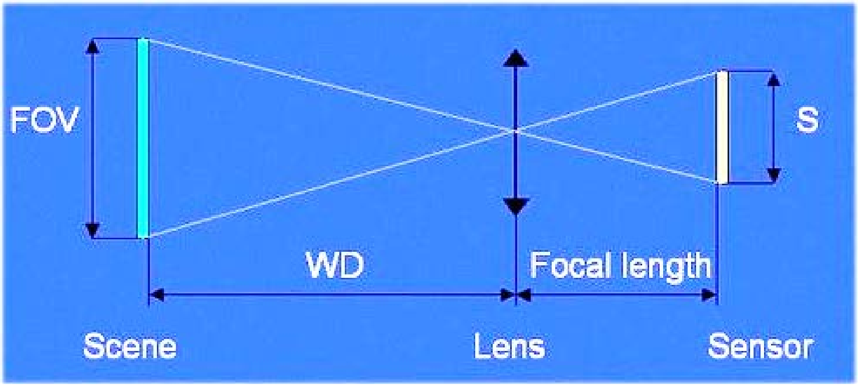

Figure 7 Field of View Diagram [36]

$$Fl = S*WD / FOV \quad [36] \qquad (1.1)$$

$$GSD = PS*WD / Fl \quad (\text{derived from } [36]) \qquad (1.2)$$

where,
Fl = focal length (mm)
S = sensor size (mm)
WD = working distance (m)
FOV = field of view (m)
GSD = ground sample distance (m)
PS = pixel size (mm)

GSD can also be found through angle of view (AOV) calculations, using Equation (1.3). Yet if the AOV is not provided, it can still be found with the sensor size and focal length, shown in Equation (1.4).

$$GSD = 2*WD*\tan(AOV / 2) \quad (\text{derived from } [37]) \qquad (1.3)$$

$$AOV = 2*\operatorname{atan}(S / 2*Fl)*180 / \pi \quad (\text{derived from } [38]) \qquad (1.4)$$

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[7] The altitude range was derived from the desire to maximize the sensor footprint at high altitudes, while staying below the radiation belt to avoid unnecessary constant radiation exposure.

where,
AOV = angle of view (in degrees)

With information on the sensor’s focal length, aperture diameter, wavelength range, and desired resolution, the sensor is analyzed for diffraction limits. Equation (1.5) is used to calculate the diffraction limited angle that is then entered into Equation (1.3) to find diffraction limited resolution of the sensor. The resulting effective resolution of the instrument is the greater of the two resolution calculations, either geometrically limited by the pixels in Equation (1.2) or diffraction limited by the aperture diameter in Equation (1.5).

$$AOV = (1.22*\lambda*/ D)*180 / \pi \qquad \textit{(derived from [39])} \qquad (1.5)$$

where,
λ = largest wavelength of sensor (mm)
D = aperture diameter (mm)

The data rate of each sensor is dependent on how it will be used in operations. The instruments will measure weather phenomena by capturing images at a low frame rate, a high frame rate, or scanning across track. In order to have complete coverage, the instruments capturing images at a low frame rate need to have some overlap. This percentage could be set as low as 1% to claim full coverage, but it was decided to set the overlap at 25% to ensure consistent resolution across the image and to allow a trade space if data rates needed to be reduced to meet downlink, crosslink, or data storage limitations. The duty cycle can be calculated using Equation (1.6). The images per orbit for the instruments that have 25% overlap can be calculated using Equation (1.7), where Earth’s polar circumference is 40,008 km. Equation (1.8) produces the operational data rate.

$$DC = (I / T) \qquad \textit{(derived from [40])} \qquad (1.6)$$

$$I = 40008\ km / (0.75*FOV) \qquad (1.7)$$

$$DR = DC*B \qquad (1.8)$$

where,
DC = duty cycle (percent is 100*DC)
I = images per orbit
T = period of orbit (sec)
DR = data rate (kbps)
B = kbits per image

Once the duty cycle is calculated, the operational power consumption is found with Equation (1.9).

$$P_{DC} = P_{TOT}*DC \qquad (1.9)$$

where,
P_{DC} = duty cycled power requirement (W)
P_{TOT} = total power for operation (W)

Most of the key values needed to design the payload sensor suite can be calculated with Equations (1.1) through (1.9). The results of these calculations are found in the component level trade study, found in Chapter IV.

3.3.3 Component Level Trade Study

The component level trade studies, with results discussed in section 4.3.3, took the subsystem requirements and budgets and compared them to available COTS components. The components that did not meet all of the constraints were rejected. The success criteria gave the highest weighting to the components with a Technology Readiness Level (TRL) above 6, where the subsystem is demonstrated in a relevant space environment, because this validation inspires confidence that the component will likely not fail. While components with the lowest mass, volume, or power consumption received less weighting because they are simply a maximum to limit the design to a CubeSat form factor, and, if optimized at the component level, they offer little benefit to overall mission success. The next section describes the cost estimation models used to approximate the WeatherSat constellation program cost.

3.3.4 Program Costs

The team calculated total satellite cost by simply summing the estimates for subsystem hardware and software costs and adding a 30% margin for labor associated with the development and manufacturing of the WeatherSat. After each satellite cost was properly estimated, published launch costs and ground station costs from existing MC3 sites were added in to develop a total program cost. These launch and ground station costs were also given a 30% margin for launch deployment risk associated with a 27U chassis that has not been launched before and possible inaccuracies in cost from the expert estimate for ground station upgrade and development. The total program cost will be compared to the GOES-R state-of-the-art, weather satellite program costs in Chapter V.

3.4 Phase 3

The third phase examines the payload sensor suite design risk and offers a refined final WeatherSat design, with recommendations for future research. The risks, identified in the payload component level trade study, needed to be addressed because they affected the confidence of the quality of performance and resolution to complete the weather mission. The refined design established the confidence of performance to conclude that the WeatherSat could meet the mission requirements and expectations.

3.5 Summary

Through the methodology discussed in this chapter, the team proposed a CubeSat design and constellation scheme to accomplish the weather mission. The final focus of this research, found in Chapter IV, is to walk through the payload sensor selection for feasibility, refine the initial satellite design, and present the final WeatherSat constellation scheme and cost.

IV. Analysis and Results

4.1 Chapter Overview

This section discusses the results from the analysis of mission and derived requirements, the payload sensor considerations and the component level trade study, and also provide a summary of the bus subsystem components in the initial WeatherSat design and constellation scheme. The cost estimation will be discussed and a comparison of the WeatherSat initial design to state-of-the-art weather satellites will be detailed. The final section will refine the design to arrive at a final proposed WeatherSat design.

4.2 Phase 1 Results

The team analyzed mission requirements by prioritizing them based on what would be most valuable to the user. The results are found in Table 4, which is rearranged from Table 1 to show prioritization of the entire set of mission requirements. The top ten priorities are to geolocate each weather phenomenon within 10 km, have resolution comparable to state-of-the-art weather satellites, capable of storing collected data before download within 30 minutes of detection, and have revisit rate under 30 minutes. The lower priority mission requirements include: to downlink through the Mobile CubeSat Command & Control (MC3) ground stations, use standard CubeSat “U” form factor, have satellite bus cost less than $500 thousand, and launch with cost less than $1 million.

Table 4 Prioritized Mission Requirements [41]

Name	Description	Priority
Cloud Detection	The system shall detect and locate clouds to within 10 km	1
Temperature Mapping	The system shall detect and map temperatures to within 10 km	2
Precipitation	The system shall detect and locate precipitation to within 10 km	3
Rapid Download	They system shall be capable of downloading all data within 30 minutes of detection	4
World Wide Coverage	The system shall have < 30 minutes revisit rate at any location in the world (threshold), or continuous coverage (objective)	5
Wind/Ocean Currents	The system shall detect and locate wind/ocean currents to within 10 km	6
Sea State	The system shall detect and locate sea state to within 10 km	7
Lightning Detection	The system shall detect and locate lightning to within 10 km	8
Data Storage	They system shall be capable of storing all collected data between downlinks	9
Resolution	The system shall be comparable to state of the art systems	10
Ground Station	The system shall use the MC3 University Network	11
Form Factor	The satellite shall conform to standard “U” form factor	12
Satellite Cost	The satellite bus (not including payload or propulsion) shall cost less than $500K per satellite	13
Launch Cost	The launch system shall cost less than $1M per satellite	14

Next, the system functional and non-functional requirements were developed to meet the mission requirements. Figure 8 and Figure 9 show the functional and non-functional requirements, respectively, as created in the Enterprise Architect tool. The functional requirements include: specific ground separation distance needed for required resolution requirement, propulsion capabilities to maintain orbit for coverage requirement, onboard data processing for data downlink requirement, 3-axis control for geolocation requirement, and data storage specifics for the storage requirement. The specific values in Figure 8 were refined over the course as new information was revealed through research. The system non-functional requirements include: mass limits according to CubeSat unit form factor and orbital specifications to meet the coverage requirement. These derived requirements can be traced back to the original mission requirements through the Traceability Matrix, as seen in Table 5.

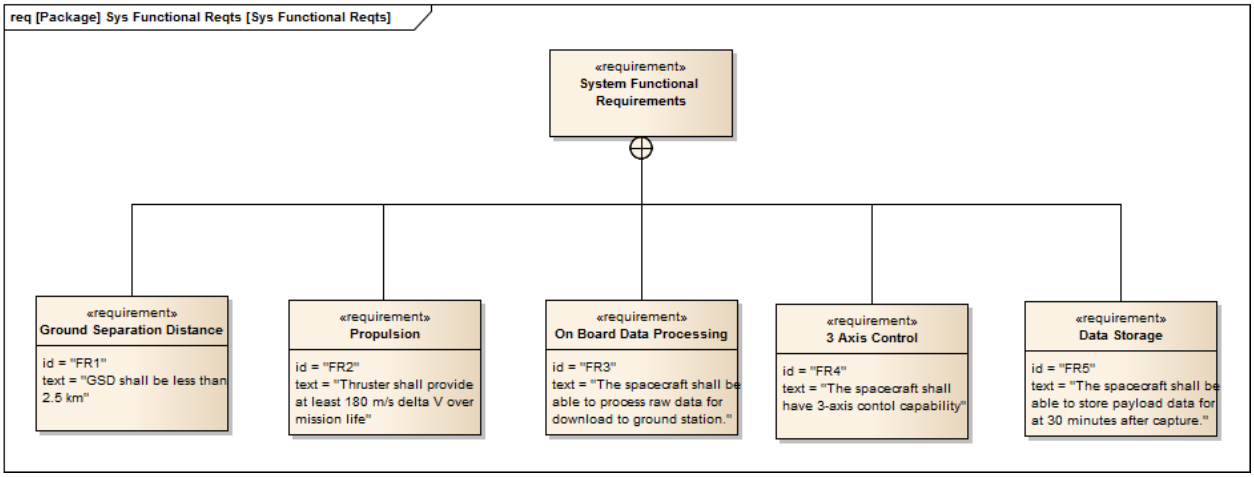

Figure 8 System Functional Requirements [42]

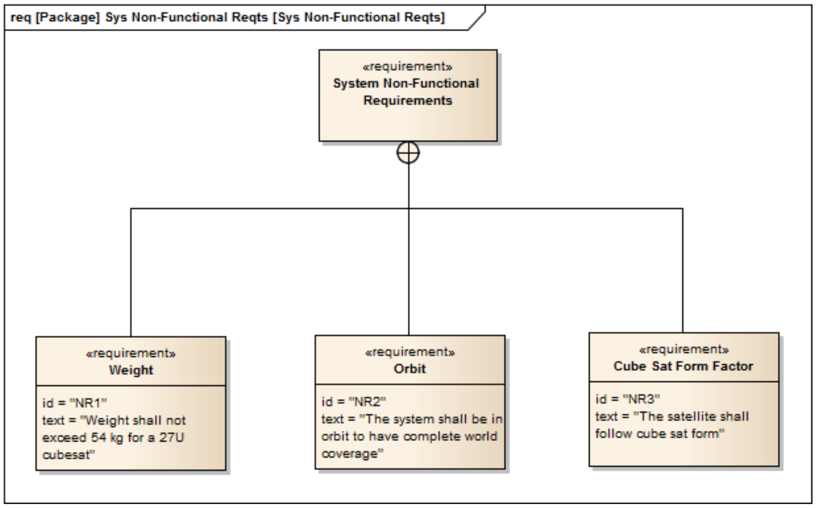

Figure 9 System Non-Functional Requirements [42]

Table 5 Traceability Matrix [42]

Derived Requirements	**Mission Requirements**														
	Cloud Detection	Temperature Mapping	Precipitation Measurement	Rapid Download	World Wide Coverage	Wind Profiling	Ocean Current Measurement	Sea State Detection	Lightning Detection	Data Storage	Resolution	Ground Station	Form Factor	Satellite Cost	Launch Cost
3-Axis Control	✓	✓	✓			✓	✓	✓	✓					✓	
Command Uplink												✓		✓	
Crosslink				✓										✓	
CubeSat Size													✓		✓
CubeSat Mass													✓		✓
Data Storage Capacity										✓				✓	
Downlink				✓										✓	
Ground Separation Distance	✓	✓	✓			✓	✓	✓	✓	✓	✓				
On Board Data Processing				✓						✓		✓		✓	
Orbit					✓						✓				✓
Propulsion														✓	✓
Revisit Rate					✓										

The team used statistical data on Low Earth Orbit (LEO) satellites [35] to begin the process of allocating technical budgets to each of the subsystems. The reference included data on mass and power budgets for satellites that are larger by a magnitude or more. The difference in size, as well as the mission and types of subsystems were identified and adjusted for WeatherSat allocations. The power allocation differences concerned the high requirement of the WeatherSat crosslink that borrowed from the payload allocation. The total power available was set to 60W due to the surface area available with deployed solar panels. The team decided to go with crosslinking instead of additional ground stations, so the power allocation had to cut into another subsystem. As for the mass allocations, the main difference was in the choice to allocate a quarter of the mass budget to use for propulsion options. The WeatherSat was to be launched on the upper end of the LEO altitude range near 1000 km for the largest sensor footprint, and this would require additional fuel to de-orbit. The statistical data showed the typical allocation for propulsion mass was 3%, which did not include the mass of the fuel as well. The overall mass was projected to be more than what a standard 12U chassis supports, so the mass and volume values are based on a 27U sized CubeSat at 54 kg [43]. Volume budgets were not included in the textbook reference, so the team estimated the volume allocations from other nanosatellite missions and component specifications. All other adjustments came from design iterations as new component information was available. The final allocations for mass, volume, and power values of each subsystem are listed in Table 6, Table 7, and Table 8.

Table 6 WeatherSat Mass Allocations (adapted from [35])

Subsystem	%	Allocated (kg)	30% Margin (kg)	Total (kg)
Payload	20.0%	7.6	3.2	10.8
Structure & Mechanisms	20.0%	7.6	3.2	10.8
Thermal Control	1.0%	0.4	0.2	0.5
Power (incl. harness)	20.0%	7.6	3.2	10.8
Telemetry, Tracking and Command (TT&C)	3.0%	1.1	0.5	1.6
On-Board Processing	4.0%	1.5	0.6	2.2
Attitude Determination & Control	5.0%	1.9	0.8	2.7
Propulsion (+ Propellant)	24.0%	9.1	3.9	13.0
Other (balance & launch)	3.0%	1.1	0.5	1.6
Total On-Orbit Mass	100%	37.8	16.2	54.0

Table 7 WeatherSat Volume Allocations [44]

Subsystem	%	Allocated (U)	30% Margin (U)	Total (U)
Payload	20.0%	3.8	1.6	5.4
Electrical Power Subsystem (EPS) Control	7.0%	1.3	0.6	1.9
Battery (incl. harness)	15.0%	2.8	1.2	4.1
TT&C	3.0%	0.6	0.2	0.8
Antenna	10.0%	1.9	0.8	2.7
On-Board Processing	5.0%	0.9	0.4	1.4
Attitude Determination & Control	20.0%	3.8	1.6	5.4
Propulsion	20.0%	3.8	1.6	5.4
Total Volume Allocation	100%	18.9	8.1	27

Table 8 WeatherSat Power Allocations (adapted from [35])

Subsystem	%	Allocated (W)	30% Margin (W)	Total (W)
Payload	20.0%	8.4	3.6	12.0
Structure & Mechanisms	0.0%	0.0	0.0	0.0
Thermal Control	10.0%	4.2	1.8	6.0
Power (incl. harness)	12.0%	5.0	2.2	7.2
TT&C	30.0%	12.6	5.4	18.0
On-Board Processing	10.0%	4.2	1.8	6.0
Attitude Determination & Control	15.0%	6.3	2.7	9.0
Propulsion	3.0%	1.3	0.5	1.8
Total On-Orbit Power	100%	42.0	18.0	60.0

4.3 Phase 2 Results

With the completion of requirements analysis and allocations set for the subsystems, each team member performs individual research on their subsystems. This section will focus on the results of the payload considerations and component level trade study, and then summarize the team’s results in the overall initial WeaterSat constellation design and program costs.

4.3.1 Payload Sensor Considerations

Following the order of weather phenomena as presented in Chapter II, this section will step through the possible sensors for the CubeSat constellation. The main considerations for each sensor are mass, volume, power, and resolution, where a sensor type was considered feasible if it stayed within 50% of the total allotted values for the payload subsystem because there are multiple components of comparable size to fit within the constraints of a CubeSat. Those totals are 10.8 kg, 5.4 U, and 12 W, so the feasibility threshold is 5.4 kg, 2.7 U, and 6 W. In section 4.3.2, the totals will be broken down into technical budgets for each sensor type to decide the best component.

4.3.1.1 Lightning Detection

Lightning detection has been measured through visible devices alone, such as with the Optical Transient Detector (OTD) and Tropical Rainfall Measuring Mission (TRMM) LIS, or through the combination of visible devices and Very-High Frequency (VHF) instruments, as is found with the Fast On-orbit Rapid Recording of Transient Events (FORTE) satellite. Yet these instruments are too large, too heavy, and consume too much power to fit a CubeSat [45], [46]. The desire is to find miniaturized sensors that can get the same resolution, but be compact enough for a CubeSat. The miniaturized VHF option requires an antenna of 33 cm or longer [47], which fails to fit the dimensions of a CubeSat. The desired type of sensor to detect lightning is a visible imager, as miniature options are available that fall well within the mass, volume, and power limits. One such visible camera is the Basler Ace acA640-120gm/gc [48], which is part of the component level trade study of Chapter IV. The Basler Ace camera is 145 g, will use an average of 2.3 W, and is a 4 cm cube.

4.3.1.2 Detection of Cloud Formations

There is a plethora of information that can be gleaned from cloud characteristics at many wavelengths. Where there are clouds, there is a loss of visibility, possibility of precipitation, development of thunderstorms with lightning, and evidence of wind and temperature profiles.

All of the potential sensors for the collection of cloud data can be miniaturized. These sensors include: a visible imager, an infrared (IR) radiometer, and a microwave radiometer. Yet not all of them can be supported on a CubeSat platform due to the limited available power on CubeSats, typically around 60 W. It would be ideal to measure cloud formations in the Mid Wave Infrared (MWIR) range as well as the Long Wave Infrared (LWIR) range to capture the spectrum of temperature characteristics, but the MWIR radiometers need to be actively cooled. MWIR radiometers require about 8W to operate and perform active cooling [49], which violates the power success criteria for a single sensor of 6W. As for the cooling requirements of a LWIR sensor, an uncooled microbolometer radiometer measures signals in the LWIR range and does not require cooling.

Since the microwave wavelength measures precipitation and not the cloud itself, it will not be a part of the sensors candidates for cloud detection. The visible camera and LWIR radiometers are sufficient for cloud formation detection, and will be included in the payload sensor suite if system level constraints can be met. A possible option for a miniaturized LWIR radiometer is the FLIR Tau 640 [50]. The FLIR microbolometer radiometer is a 4.5 cm cube of 150 g mass, and with duty cycling will need an average of 0.6 W.

4.3.1.3 Temperature Profiling

Temperature variations can be measured in the IR and microwave ranges. Ground and lower atmosphere temperatures can be measured in the MWIR and LWIR range, where mid to upper atmosphere temperature profiles are read in the LWIR and microwave ranges. It seems like a simple choice to use a LWIR instrument to measure all altitudes, but then the LWIR instrument would have to be an instrument of hundreds of channels, which does not come in miniature form. One such instrument, the Cross-Track Infrared Sounder (CrIS), is an IR sounder on the Suomi National Polar-orbiting Partnership (SNPP), which weighs 85 kg and uses up to 124 W [51]. This instrument is not suited for a CubeSat, so there will have to be two miniaturized sensors to measure temperature in both the lower and upper atmospheres.

As discussed in section 4.3.1.2, a MWIR radiometer requires too much power for active cooling of its focal array. This leaves a LWIR microbolometer radiometer as the sensor of choice for ground and low atmosphere temperature readings.

For mid and upper atmospheric temperature measurements, there are two methods that capture data in the microwave range and can collect through multiple altitudes. The first is a passive microwave radiometer, which has recently been miniaturized in the nanosatellite projects of Micro-sized Microwave Atmospheric Satellite (MicroMAS) and Microwave Radiometer Technology Acceleration (MiRaTA). The payload is 1 kg, is takes up less than 2U of volume, and is powered by about 3W. The second option is to use radio occultation in the Global Positioning System (GPS) frequency, which has been a contributor to weather observations since 2007 [52]. The GPS receiver needed to perform this method of measurement is well within the limitations of a CubeSat, yet the poor accuracy in the stratosphere and warmer climates, need of external data to calibrate measurements, and lack of horizontal resolution, makes it a poor choice for this weather mission [53]. In comparison to the incomplete data offered by radio occultation, microwave radiometers, such as the Advanced Microwave Sounding Unit (AMSU), are the leading contributors to weather forecasting [52].

The ideal pair of sensors to measure temperature at all altitudes and still fit the constraints of a Cubesat are the LWIR microbolometer radiometer and passive microwave radiometer, where the LWIR radiometer measures temperature at low altitudes, and the microwave radiometer collects temperature profiles in the upper atmosphere. The LWIR microbolometer radiometer has the added benefit of detecting cloud formations, so the payload sensor suite has only added a microwave radiometer.

4.3.1.4 Measurement of Precipitation

Precipitation can be detected with IR sensors, microwave sensors, as well as through the method of scatterometry. The IR sensor and scatterometry fall short of accurately measuring all precipitation and rates. IR sensors are used to estimate precipitation rates based on cloud signatures. As discussed in section 2.2.4, the IR sensor has poor accuracy with non-precipitating high-altitude clouds and low-altitude warm rain clouds. Also, scatterometry for precipitation readings is inaccurate for low rain rates.

Since these sensors are not reliable across the spectrum of precipitation, they will not be the recommended choice for precipitation measurements.

Microwave sensors directly measure precipitation through scattering and emission signatures. This wavelength sees through clouds and can read rain rates over land or sea accurately. Also, ice signatures scatter in the microwave band, making this sensor ideal for snow detection. There is a weakness in accuracy when there is an abundance of cloud coverage and snow-covered land, but overall a microwave sensor is the best choice.

4.3.1.5 Measurement of Sea State

In Chapter II, it states that sea state measurements are typically made using the microwave wavelength through scatterometry and with an altimeter for sea height. Poseidon-3 is an altimeter on Jason-2, which has a peak power output at 8 W for Ku-band and 25 W for C-band [54]. This sensor does not meet the technical budgets of mass, volume, and power. The remaining options are between active and passive microwave radiometers with polarization or using GPS signals for scatterometry. Unfortunately, there are not miniaturized active microwave radiometers. The typical sensor, such as SeaWinds on QuikSCAT, is about 200 kg and uses 250 W of power [55]. There are passive microwave radiometers, such as MiRaTA, which are miniaturized. Yet these instruments lack polarization. Polarization could be achieved through adding multiple feedhorns or using two sensors of opposite polarization in the same satellite. There is no information available on the sizes of multiple feedhorns per sensor or the associated added complexity and risk, so this option is rejected. Also, it is best to go with an option that only requires one sensor to operate, as the goal is to reduce the cost and satellite size needed to complete the weather mission. The optimal sensor for sea state measurements therefore is the GPS receiver, employing a scatterometry method. An example GPS receiver, part of the component level trade study in Chapter IV, is the Surrey SGR-05U [56]. It operates on 0.8 W of power, is 110 g, and has a 7 cm long board with an antenna length of 4.5 cm.

4.3.1.6 Wind Profiling

Wind profiles are difficult to accurately measure. They can be estimated through ocean surface measurements with microwave scatterometry, but that will not be useful over land or through all altitudes. The wind profiles in the atmosphere can be estimated by modeling temperature profiles and then detecting cloud movement in the visible range can estimate wind over land. All of these observations provide a complete picture of wind profiles. The optimum payload suite would have a GPS receiver to perform scatterometry for wind over the ocean, LWIR microbolometer radiometer and visible camera for wind measurements over land, and finally a microwave radiometer to calculate wind profiles at higher altitudes. This works out well due to the mission requirement to measure sea states, map temperature, and detect cloud formations, which already call for these instruments. No new sensors are required to meet the mission requirement to measure wind.

4.3.1.7 Ocean Current Detection

Similarly to calculations needed to extract wind profiles, ocean currents depend on measurements of other sea characteristics to estimate them. State-of-the-Art methods utilize IR sensors, radio scatterometry, and sea height measurements through altimetry.

The first two methods are feasible on a CubeSat, but altimetry readings require active sensors. Currents are comprised of large masses of water with similar temperature [18], so using a LWIR microbolometer radiometer will capture most of the data needed to monitor ocean currents. A GPS receiver can provide additional information about the sea surface to aid in ocean current detection. No new sensors are required to meet the mission requirement to detect ocean currents.

4.3.1.8 Summary of Payload Sensor Considerations

The sensor suite considered for the initial design of the WeatherSat is comprised of the following sensors: 1) visible/near infrared camera, 2) long wave infrared microbolometer radiometer, 3) passive microwave (MW) radiometer, and 4) GPS receiver for scatterometry measurements. Also, there will need to be ground processing support to calculate wind profiles and ocean currents from the data collected, which will not be attempted onboard the WeatherSat. Table 9 depicts the considered sensors and methods of measurement for each of the weather phenomena and shows the recommended sensors chosen for the component level trade study in section 4.3.3. All four of the chosen sensors measure more than one weather phenomena, which is summarized in Table 10.

Table 9 Sensor Suite Recommendation for Initial Design

Weather Phenomena	Sensor/Method Options	Recommendation
Lightning	Visible camera VHF instrument	Visible camera
Cloud Formation	Visible camera MWIR radiometer LWIR microbolometer radiometer MW radiometer	Visible camera LWIR microbolometer radiometer
Temperature Mapping	MWIR radiometer LWIR microbolometer radiometer LWIR sounder Passive MW radiometer GPS Occultation	LWIR microbolometer radiometer Passive MW radiometer
Precipitation	LWIR microbolometer radiometer Passive MW radiometer Active MW radiometer GPS scatterometry	Passive MW radiometer
Sea State	MW radiometer GPS scatterometry	GPS scatterometry
Wind Profiles	Visible camera LWIR radiometer Passive MW radiometer GPS scatterometry	Visible camera LWIR microbolometer radiometer Passive MW radiometer GPS scatterometry
Ocean Currents	LWIR radiometer GPS scatterometry Altimeter	LWIR microbolometer radiometer GPS scatterometry

Table 10 Overlapping Weather Phenomena Measurements

Weather Phenomena	Initial Sensor Suite			
	Visible camera	LWIR microbolometer radiometer	Passive MW radiometer	GPS receiver for scatterometry
Lightning	✓			
Cloud Formation	✓	✓		
Temperature Mapping		✓	✓	
Precipitation			✓	
Sea State				✓
Wind Profiles	✓	✓	✓	✓
Ocean Currents		✓		✓

The analysis of a possible sensor suite was crucial to establish first, as it validated and shaped further subsystem level requirements. The constellation scheme relied on payload characteristics, such as the smallest estimated angle of view (AOV) of 60 degrees. A satellite analysis program, Systems Tool Kit (STK) by Analytical Graphics Inc., was used to evaluate the footprint coverage with the 60 degrees AOV and analyze ground station placement for downlinking. Adding the MC3 ground station locations to the simulation, it was immediately evident that the mission requirement of 30 minutes to downlink data collected would not be met unless there was an increase of satellites, ground stations, or orbit height. These options exceeded cost and resolution requirements, so another capability of crosslinking data through adjacent satellites to reach the ground stations within 30 minutes was explored by the team.

4.3.2 Payload Budgets

The team now has a candidate sensor suite, subsystem allocations, and an understanding of the constellation needs to make this mission successful. The component level trade studies dove into specific components that fit the constraints and developed a plan to create a constellation given mission requirements.

The payload subsystem has a mass, volume, and power budget (Table 6, Table 7, and Table 8), but there are other requirements that must also be divided amongst the subsystems. There is a geolocation mission requirement, which requires the WeatherSat to determine the weather phenomena location to within 10 km. Determining location is accomplished jointly through resolution of the payload sensor and pointing accuracy of the Attitude Determination and Control Subsystem (ADCS). The ADCS was given a notional angle error of 0.25 degrees as its maximum pointing error, which is reasonable for many COTS attitude determination sensors. From the 0.25 degree pointing error and

800 km altitude, the geolocation constraint was divided up into 3.5 km requirement for ADCS and a 6.5 km resolution requirement for the payload sensors [41]. The payload component level trade study will compare all four sensors to a constraint of 6.5 km. In section 4.3.3.5, the inconsistency between the geolocation requirement and resolution requirement to meet state-of-the-art standards will be discussed. Another system level requirement, which placed constraints on the payload, was the need to set the amount of data being collected for crosslink and eventual downlink. So, a nominal data rate for the suite of four sensors was set to less than 75 kbps based on component specifications. 75 kbps became the data rate value to determine the crosslink requirements and design.

Besides divvied requirements between subsystems, the payload sensors must also have budgeted requirements. The sensor suite is tentatively comprised of four sensor types that have the mass, volume, power, and data rate budgets given in Table 11.

Table 11 Sensor Budgets

Sensor Type	**Mass (kg)**	**Volume (U)**	**Power (W)**	**Data Rate (kbps)**
Visible camera	2.6	1.25	4	30
LWIR microbolometer radiometer	2.6	1.25	2.5	35
Passive MW radiometer	4.6	2	3.5	5
GPS receiver (scatterometry)	1	0.9	2	5
Total Budget	**10.8 kg**	**5.4 U**	**12 W**	**75 kbps**

4.3.3 Component Level Trade Studies

The payload sensor trade study compares specifications about COTS components against the constraints and one another to select the best sensor for the payload sensor suite. The desire is to select the components with the highest Technology Readiness Level (TRL) that still meet the budget constraints. The component trades study will begin with the visible camera, then the LWIR microbolometer radiometer, the passive microwave radiometer, and end with the GPS receiver for scatterometry measurements. A description of the initial payload sensor suite is in section 4.3.3.5.

4.3.3.1 Visible Camera

A visible camera will be used to detect lightning and cloud formations. These two weather phenomena require different duty cycles to collect the proper data. For lightning detection, the camera must have a high frame rate to sense a change in brightness. Although the camera is capturing many images to decide if a lightning flash occurred, it does not need to store the unnecessary images without lightning flashes. Collecting data on cloud formations requires the camera to take an image once per view with an overlap of 25%. The outcome of this method of operation is a data generation rate lower than what is documented in the components specifications.

Besides the budgets summarized in Table 11, the visible cameras researched are graded on if they meet the resolution requirement of 6.5 km and do not have a limiting operational temperature range (5 to 30 degrees Celsius of the batteries). There are many COTS solutions for visible cameras. In order to compare them, the cameras chosen for the study had a focal plane array near 640x480 in size, met or exceeded 90 degrees in angle of view (AOV) in one direction, and were similar volume when pairing a lens to reach proper resolution. The resulting choices for possible visible cameras are shown in Figure 10, Figure 11, Figure 12, and Figure 13.

Figure 10 Basler Ace acA640-120gm/gc (GigE) with 6mm lens [48]

Figure 11 Baumer TXG02c (GigE) with 6mm lens [57]

Figure 12 Teledyne Dalsa Genie HC640 (GigE) with 6mm lens [58]

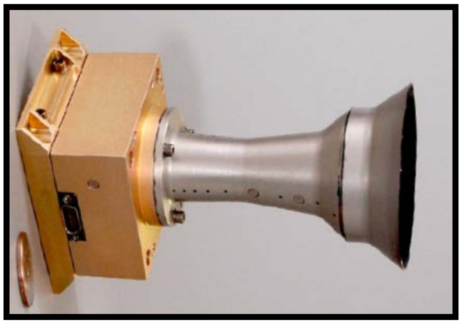

Figure 13 Malin Space Science Systems ECAM-C30 WFOV [59]

The trade study is summarized in Table 12, with the Malin Space Science Systems camera as the selected component. Only one of the components did not meet all of the budgeted limits, which was the camera by Baumer. The selected camera met all of the requirements, while having the best resolution (not diffraction limited [59]). In addition to these characteristics, the ECAM optics are built to withstand launch hazards and to be used in orbit long-term. A version of the ECAM-C30 will be launched on the OSIRIS-Rex satellite to research an asteroid in September 2016 [60], which will raise its TRL to an 8. The other sensors did not have evidence of being validated in a space environment, so they are estimated to be at a TRL of 4.

Table 12 Visible Camera Trade Study [44]

Name of Component	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 2.6 kg	< 1.25 U	< 4 W	< 30 kbps	< 6.5 km	Not limiting	Not specified [8]
Basler Ace - acA640-120gm/gc (GigE) w/ 6mm lens [48]	0.145 kg	0.05 U (plus lens)	2.3 W	28.5 kbps	1.5 km	0 C to 50 C*	$650 (plus lens)
Baumer TX-Series - TXG02c (GigE) w/ 6mm lens [57]	.09 kg (plus lens)	0.06 U (plus lens)	3.6 W	32.7 kbps	1.5 km	5 C to 50 C*	$830
Teledyne Dalsa Genie - HC640 (GigE) w/ 8mm lens [58]	0.115 kg (plus lens)	0.09 U (plus lens)	4 W	18.3 kbps	1.5 km	0 C to 45 C*	$1,960
Malin Space Science Sys ECAM-C30 WFOV [59], [60]	0.346 kg	0.51 U	2.5 W	28 kbps	1 km	-20 C to 40 C*	No info (est. $4.2K)

* No information on survival temperature ranges.

4.3.3.2 Long Wave Infrared Microbolometer Radiometer

A long wave infrared (LWIR) microbolometer radiometer will be used for a majority of the measurements, in cloud detection, ground and ocean surface temperature measurements, and the calculations needed to find wind over the oceans and ocean currents. All of these measurements only require this sensor to take images with a 25% overlap. Therefore, the duty cycle of about 1% has greatly reduced the data rate and power consumption of the LWIR microbolometer radiometer for the WeatherSat. Along with the budgets set in Table 11, the radiometers found for the trade study must meet the resolution requirement of 6.5 km and do not have a limiting operational temperature range (5 to 30 degrees Celsius of the batteries). Like the visible camera options, the radiometers chosen had the same focal plane array size, AOV, and GSD. Three options were found for possible uncooled LWIR microbolometer radiometers, depicted in Figure 14, Figure 15, and Figure 16.

Figure 14 FLIR Tau 640 Uncooled Microbolometer [50]

Figure 15 DRS Technologies Tamarisk 640 Atherm [61]

Figure 16 Xenics Serval 640 GigE [62]

The LWIR microbolometer radiometer trade study is summarized in Table 12. Even with the drop in data rate from the duty cycling, two of the three components researched could not collect the necessary information within the data rate budgeted. The Xenics component was close, and may have been considered an option if the budgets were recalculated, but it is simply a worse choice compared to the selected component from FLIR. None of the components have been flown in space, so the FLIR radiometer is selected with risk as a TRL 4. The FLIR radiometer meets all of the constraints and is not diffraction limited [50].

Table 13 LWIR Radiometer Trade Study [44]

Name of Component	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 2.6 kg	< 1.25 U	< 2.5 W	< 35 kbps	< 6.5 km	Not limiting	Not specified [8]
FLIR TAU 2 640 w/ 7.5mm lens [50]	~ 0.15 kg (FLIR approx.)	0.1 U	0.6 W	32 kbps	1.5 km	-40 C to 80 C (surv: -55 to 95 C)	$8.2K
DRS Technologies Tamarisk 640 Atherm w/ 7.5mm lens [61]	0.10 kg	0.07 U	0.75 W	54.8 kbps	1.5 km	-40 C to 80 C*	$8.2K
Xenics Serval-640-GigE w/ 10mm lens [62]	No info (est: 0.6 kg)	0.4 U (plus lens)	2.25 W	36.6 kbps	1.4 km	0 C to 60 C*	No info

* No information on survival temperature ranges.

4.3.3.3 Passive Microwave Radiometer

A passive microwave (MW) radiometer will be used for atmospheric temperature mapping and wind profile calculations, plus precipitation measurements. The results were scarce for this sensor in the size a CubeSat can accommodate. The only systems found were a nanosatellite sensor system on the Micro-sized Microwave Atmospheric Satellite (MicroMAS) satellite and its follow-on to be flown on the Microwave Radiometer Technology Acceleration (MiRaTA). Due to the lack of COTS options, the WeatherSat passive MW radiometer will mimic the design of the two nanosatellite sensors. The MicroMAS is a 3U CubeSat, where the 1U that contains the radiometer rotates independently to scan the Earth, seen in Figure 17. In Figure 18, the MicroMAS microwave radiometer rotates along the velocity vector. It scans the Earth while the radiometer faces nadir and calibrates off of deep space when pointing zenith. The

WeatherSat will place the passive microwave radiometer and scanning assembly, without the external structure, in a nadir-facing corner of the WeatherSat, so that the radiometer can scan Earth for a quarter rotation and calibrate off Earth's horizon for another quarter rotation.

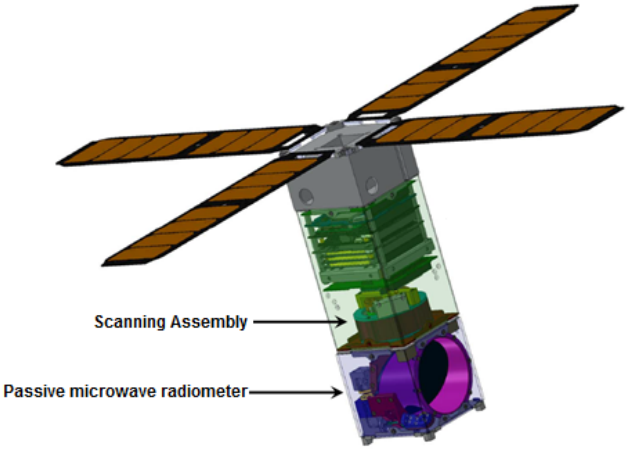

Figure 17 MicroMAS Sensor and Scanning Assembly [63]

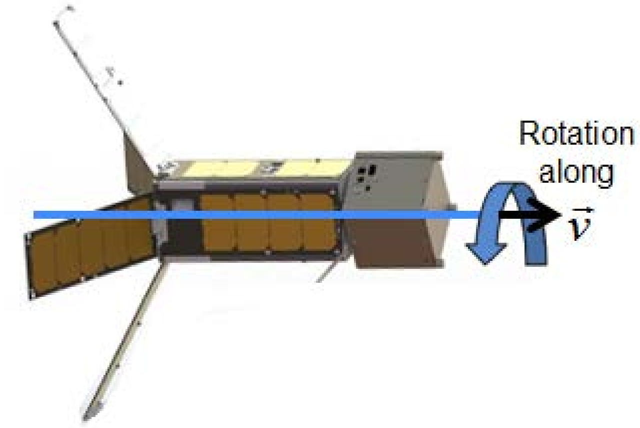

Figure 18 MicroMAS Sensor Rotation [44]

Table 14 summarizes the characteristics of the two nanosatellite payloads. Both break the resolution requirement established when the 10 km geolocation mission requirement was split into ADCS pointing accuracy and sensor resolution. From the only two options, the MiRaTA, as the improved of the two sensors, is the choice of this trade study. A great benefit to the WeatherSat mission is the higher TRL of 6 and 7 for the space operations of MicroMAS in space and the legacy system undergoing improvements for the follow-on, MiRaTA.

Table 14 Passive MW Radiometer Trade Study [44]

Name of Component	Mass (kg)	Volume (U)	Average Power (W)	Data Rate (kbps)	GSD (km)	Temp Range	Cost
Requirements	< 4.6 kg	< 2 U	< 3.5 W	< 5 kbps	< 6.5 km	Not limiting	Not specified [8]
MicroMAS Microwave Radiometer [63]	1 kg	1.5 U	1.5 W	5 kbps	31.25 km	-40 C to 60 C*	No info (est. $275K [64],[65])
MiRaTA Microwave Radiometer [64]	0.91 kg	1.8 U	3 W	No info (est. 5 kbps)	10 km	No info	No info

* No information on survival temperature ranges.

4.3.3.4 Global Positioning System Receiver for Scatterometry

A Global Positioning System (GPS) receiver will be the component used to perform scatterometry off of the ocean surface for sea state measurements and calculations for wind and ocean currents. GPS receivers are common and a couple companies even make the receivers specifically for space applications. Yet, a difficulty arises from a lack of information concerning accuracy. Typically, GPS receivers are used to locate the satellite in orbit in reference to the Earth, not for scatterometry. The information on the achievable scatterometry resolution is not published. Even when researching the successes of the United Kingdom – Disaster Monitoring Constellation (UK-DMC) satellite natural disaster relief and reading the performance expectations of the upcoming Cyclone Global Navigation Satellite System (CYGNSS) satellite to measure sea state with GPS scatterometry, there is a lack of information concerning resolution. Figure 19 and Figure 20 show images of two of the three components considered in the trade study for a GPS receiver.

Figure 19 Surrey SGR-05U Space GPS Receiver [56]

Figure 20 NovAtel OEMV-1DF Receiver [66]

Table 15 summarizes the characteristics of each component. Any of the components would suffice, but the Surrey Satellite Technology is the best choice. The sole reason that their GPS receiver was chosen over the others was due to their experience with GPS scatterometry satellite programs, with an estimated TRL of an 8. The other companies had no readily apparent information that their instrument was used for scatterometry, so it is suggested that those components are TRL of 7 or below. Surrey has instruments on both the UK-DMC [67] and CYGNSS [68]. A comparison of specifications about these satellite receivers shows that the Surrey SGR-05U will have a similar performance and can be considered on par with their success level. The SGR-05U can be considered feasible based on its similarity to other sea state scatterometry sensors, but one cannot conclude that it will specifically meet the desired resolution of 39.5 km.

Table 15 GPS Receiver Trade Study [44]

Name of Component	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 1 kg	< 0.9 U	< 2 W	< 5 kbps	< 6.5 km	Not limiting	Not specified [8]
Surrey SGR-05U [56]	0.11 kg	0.08 U	0.8 W	1.5 kbps (est)	UNK	-20 C to 50 C (surv: -30 to 60 C)	$26.3K each
SSBV Aerospace & Tech Group Space-based GPS Receiver [69]	0.03 kg	0.01 U (plus antenna)	< 1 W	1.5 kbps (est)	UNK	-10 C to 50 C*	No info
NovAtel OEMV-1DF w/ ANT-26C1GA-TBW-N antenna [66]	0.14 kg	0.12 U	1.1 W	1.5 kbps (est)	UNK	-40 C to 85 C (surv: same)	No info

* No information on survival temperature ranges.

4.3.3.5 Summary of Component Level Trade Study

The final sensor suite is summarized in Table 16, where the overall subsystem requirements and budgets are met with the exception of the resolution of the passive MW radiometer and the lack of information on the GPS scatterometry resolution. Figure 21 depicts the configuration of the sensors on the nadir-facing side of the WeatherSat.

Table 16 Trade Study Summary [44]

Name of Component	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 10.8 kg	< 5.4 U	< 12 W	< 75 kbps	< 6.5 km	Not limiting	Not specified [8]
VIS (Malin Space Science Systems ECAM-C30 WFOV [59], [60])	0.346 kg	0.51 U	2.5 W	28 kbps	1 km	-20 C to 40 C (survival: No info)	No info (est. $4.2K)
LWIR (FLIR TAU 2 640 w/ 7.5mm lens [50])	~ 0.15 kg	0.1 U	0.6 W	32 kbps	1.5 km	-40 C to 80 C (survival: -55 to 95 C)	$8.2K
MWR (MiRaTA [64])	0.91 kg	1.8 U	3 W	5 kbps	10 km	-40 C to 60 C (survival: No info)	No info (est. $275K)
GPS for Scatterometry (2 Surrey SGR-05U, other for ADCS [56])	0.22 kg	0.16 U	1.6 W	3 kbps	UNK	-20 C to 50 C (survival: -30 to 60 C)	$52.6K
Totals	**1.63 kg**	**2.57 U**	**7.7 W**	**68 kbps**	**1 km - UNK**	**-20 C to 40 C** (survival: same)	**Est. $340K**

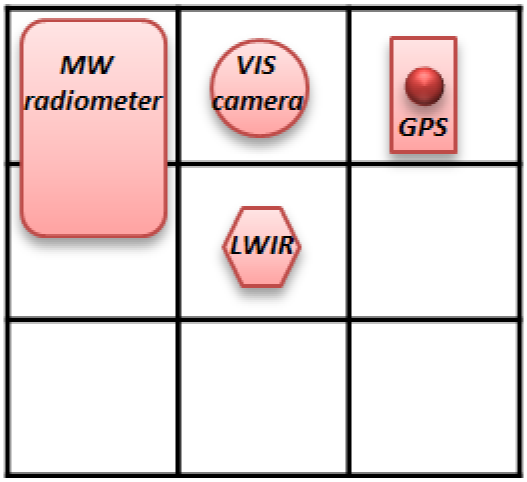

Figure 21 Payload Configuration (nadir-facing)

The sensor resolution constraint of 6.5 km was decided based on the geolocation mission requirement of 10 km, where the payload resolution and ADCS pointing error combine to meet this requirement. This isn't consistent with state-of-the-art standards of geolocation of weather phenomena. Based on the literature review of U.S. weather satellites, it was found that expected resolutions range from 0.6 km to 48 km. The four sensors are matched with the resolution expected in state-of-the-art performance in Table 17.

Table 17 Sensor Type Vs. Standard of Resolution

Weather Phenomena	Standard of Resolution Quality	Recommendation
Lightning	14 km	Visible camera
Cloud Formation	~ 0.6 km* (range: 0.5 – 0.75 km)	Visible camera LWIR microbolometer radiometer
Temperature Mapping	~ 2.4 km* (ground) (range: 2 - 2.7 km) 39.5 km (upper atmosphere)	LWIR radiometer Passive MW radiometer
Precipitation	13.5 km	Passive MW radiometer
Sea State	48 km	GPS scatterometry
Wind Profiles	39.5 km	Visible camera LWIR microbolometer radiometer Passive MW radiometer GPS scatterometry
Ocean Currents	48 km	LWIR microbolometer radiometer GPS scatterometry

* Average value is reasonable for these comparable sensors.

Table 17 shows that there can be up to four standards of resolution quality for each of the final four sensors and calculations. Instead of selecting four LWIR radiometers of differing resolution, the research was simplified to select a single LWIR radiometer that would meet the most stringent of resolution requirements. Therefore, the resolution requirements for each sensor are: 1) a visible camera with about 0.6 km resolution, 2) a LWIR radiometer at about 2.4 km, 3) a passive MW radiometer with resolution near 13.5 km, and 4) a GPS scatterometry capable of around 39.5 km resolution. The comparison of the standard for resolution against the initial payload design is captured in Table 18, shows that all of the sensors meet the standard of resolution with the exception of the GPS receiver for scatterometry.

Table 18 Sensor Resolution Requirements Vs. Design

Sensor Type	Resolution Requirement	Initial Design
Visible camera	~ 0.6 km	1 km
LWIR microbolometer radiometer	~ 2.4 km	1.5 km
Passive MW radiometer	13.5 km	10 km
GPS receiver (scatterometry)	39.5 km	Unknown

4.3.4 Initial WeatherSat Physical Design

The preliminary design has the mass, volume, and power consumption summarized in Table 19, Table 20, and Table 21. Although the team has accurate values collected from specification sheets, a 30% margin was added to account for wiring, proper spacing for integration, and to have margin for the unexpected. The preliminary proposed design falls within the mass, volume, and power limits allotted, as the total values are: 1) 30 kg mass, 2) 16.3 U volume, and 3) 41.6 W of power consumption. The 27 U design can be up to 54 kg and the solar array can produce peak power of 72 W.

Table 19 Preliminary WeatherSat Design Mass [44]

Mass	Estimate (kg)	30% Margin (kg)	Total (kg)	Percentage
Payload	1.7	0.5	2.2	7.3%
Structures & Mechanisms	6.5	2.0	8.5	28.3%
Thermal Control	0	0	0	0.0%
Power (including harness)	7.3	2.2	9.5	31.7%
TT&C	0.65	0.2	0.8	2.7%
On-Board Processing	0.25	0.1	0.3	1.0%
Attitude Determination & Control	1.1	0.3	1.4	4.7%
Propulsion (and propellant)	4.6	1.4	6.0	20.0%
Other (balance & launch)	1	0.3	1.3	4.3%
Total On-Orbit Mass	**23.1**	**7.0**	**30.0**	**100%**

Table 20 Preliminary WeatherSat Design Volume [44]

Volume	Estimate (U)	30% Margin (U)	Total (U)	Percentage
Payload	2.6	0.8	3.4	20.9%
EPS Control	1.0	0.3	1.3	8.0%
Batteries (including harness)	2.4	0.7	3.1	19.0%
TT&C	0.4	0.1	0.5	3.0%
Antenna	1.4	0.4	1.8	11.0%
On-Board Processing	0.5	0.2	0.7	4.3%
Attitude Determination & Control	1.6	0.5	2.1	12.9%
Propulsion (and propellant)	2.6	0.8	3.4	20.9%
Total On-Orbit Volume	**12.5**	**3.8**	**16.3**	**100%**

Table 21 Preliminary WeatherSat Design Power [44]

Power	Estimate (W)	30% Margin (W)	Total (W)	Percentage
Payload	7.7	2.3	10	24.0%
Structure & Mechanisms	0	0	0	0.0%
Thermal Control	0	0	0	0.0%
Power (including harness)	4	1.2	5.2	12.5%
TT&C	14.75	4.4	19.2	46.2%
On-Board Processing	1.4	0.4	1.8	4.3%
Attitude Determination & Control	4	1.2	5.2	12.5%
Propulsion	0.15	0	0.2	0.5%
Total On-Orbit Power	**32**	**9.5**	**41.6**	**100%**

The WeatherSat constellation scheme, seen in Figure 22, will consist of 198 satellites, in 11 planes of 16 satellites and 2 spares each. They will be launched 6 at a time, by the Pegasus launch vehicle, into a Walker constellation scheme of an 800 km altitude and 85 degree inclination. This configuration requires crosslinking, depicted in Figure 23, to enable the data to be downlinked within 30 minutes, while providing a 4 minute revisit time. The MC3 network will have improved S-band and four more sites will have to be built to complete the mission.

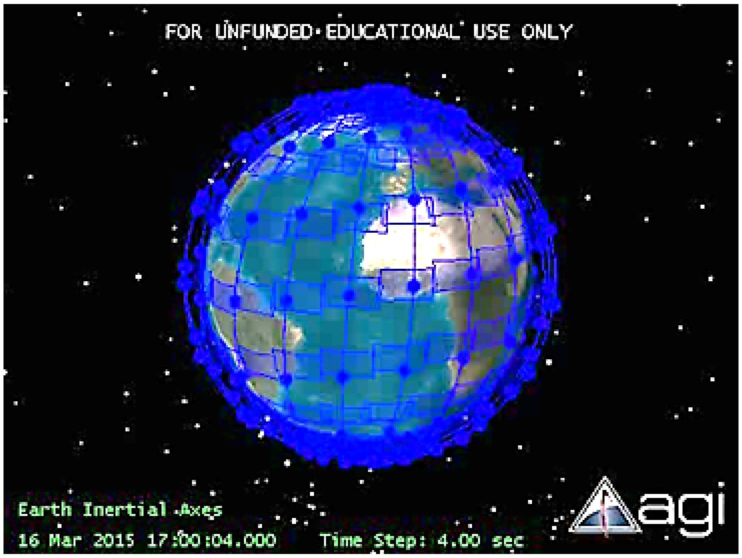

Figure 22 WeatherSat Constellation Scheme [44]

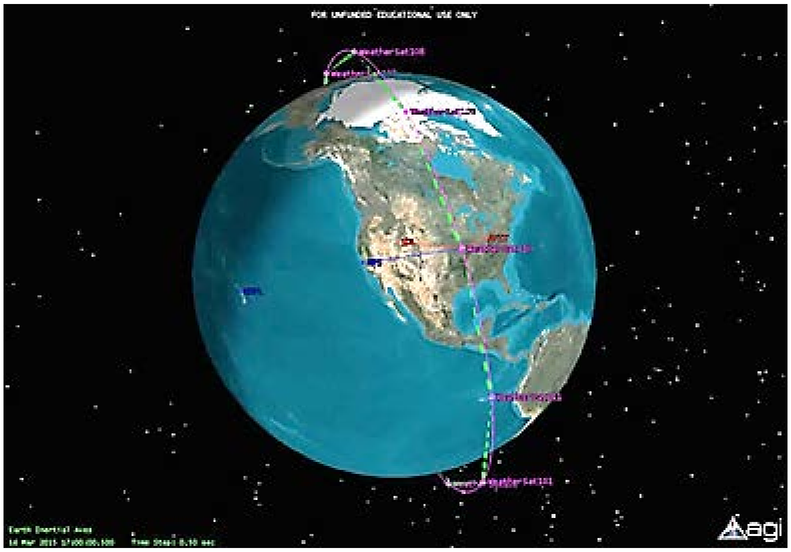

Figure 23 Crosslink within Plane [44]

Based on the research of the other team members, the payload design is integrated into a 27U CubeSat bus, depicted in Figure 24, containing the subsystem components described in sections 4.3.4.1 through 4.3.4.5 [41].

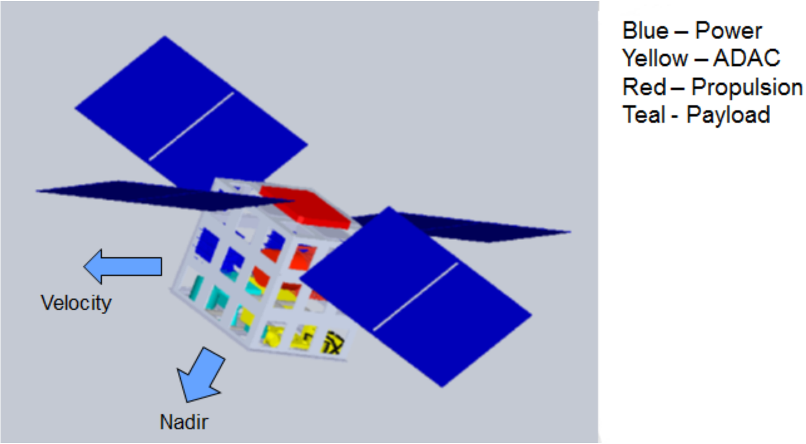

Figure 24 27U WeatherSat Design [44]

4.3.4.1 Electrical Power Subsystem (EPS)

The Electrical Power Subsystem (EPS) consists of batteries with a control board, seen in Figure 25 and Figure 26, and solar panels. The solar panels are custom, the E-HAWK Nanosat Series by MMA Design, and consist of 8 panels to expand from four of the WeatherSat sides. The solar panels can provide up to 72 W peak power, covering the 42 W peak power expected from the WeatherSat. The battery and board are products of Clyde Space. There will be 10 CS-SBAT2-30 batteries and a custom board to meet the mission needs of 290 W-hours.

Figure 25 Clyde Space Batteries [44]

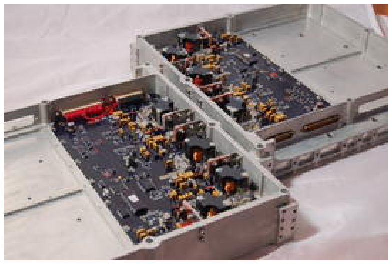

Figure 26 Clyde Space EPS Board [44]

4.3.4.2 Attitude Determination & Control Subsystem (ADCS)

The Attitude Determination & Control Subsystem (ADCS) has an Earth and Sun sensor (Figure 27 and Figure 28), a magnetorquer and magnetometer (Figure 29 and Figure 30), a receiver and board, and reaction wheels (Figure 31). The components are from a variety of vendors known for nanosatellite components. The single Earth sensor, by Maryland Aerospace, and three Sun sensors, from SSBV Aerospace & Technology Group, meet the required pointing accuracy of 0.25 degrees. The three reaction wheels are the Sinclair RW-0.03-4 for 30mNm-s to meet the momentum needs. Clyde Space products will be used as the CS-ADCS-INT-01 board and Z-Axis magnetorquer, with a magnetometer from SSBV about the size of a penny. Another Surrey Satellite Technologies GPS receiver, which was used for scatterometry on the nadir face, will be employed for geolocation on the zenith side.

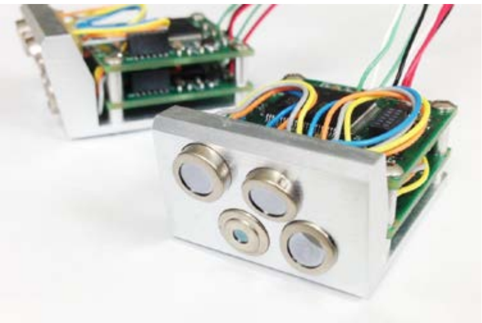

Figure 27 Maryland Aerospace Static Earth Sensor [41]

Figure 28 SSBV Fine Sun Sensor [41]

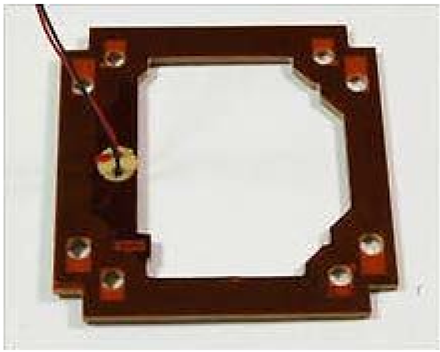

Figure 29 Clyde Space Z-Axis Magnetorquer [41]

Figure 30 SSBV Magnetometer [41]

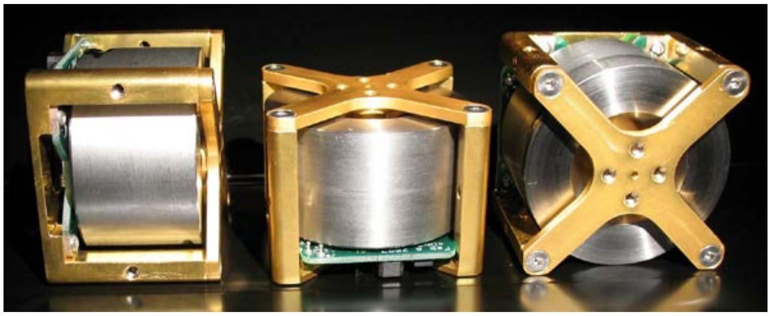

Figure 31 Sinclair RW-0.03-4 Reaction Wheels [41]

4.3.4.3 Propulsion Subsystem

The Propulsion Subsystem is made of a monopropellant thruster and terminator tape for de-orbit, seen in Figure 32 and Figure 33. The green monopropellant thruster by Busek will provide 60 m/s of delta-V to meet the 52 m/s necessary to perform orbit phasing for constellation spacing. The passive de-orbiter, NanoSat Terminator Tape, is used from Tether's Unlimited to passively de-orbit within the 25 year window allowed by the U.S. Government Orbital Debris Mitigation Standard Practices.

Figure 32 Busek Green Monopropellant Thruster [44]

Figure 33 Tethers Unlimited NanoSat Terminator Tape [44]

4.3.4.4 Telemetry, Tracking and Command (TT&C) Subsystem

The Telemetry, Tracking and Command (TT&C) Subsystem consists of an S-band receiver/transmitter for uplink/downlink and a separate transmitter for S-band crosslink. Improvements to the Mobile CubeSat Command & Control (MC3) S-band network, as well as four new sites, are necessary to downlink the data within 30 minutes. Tethers Unlimited SWIFT-SLX components will be used for uplink/downlink, and Spacequest's TX-2400 components will be used for crosslink needs.

4.3.4.5 Command and Data Handling (CD&H) Subsystem

The Command and Data Handling (C&DH) Subsystem has an industrial rated processor. The processor is an Air Force Institute of Technology (AFIT) customized product, called BeagleBone Black (Figure 34), with 32 GB memory capacity and speed of 1 GHz. The team members estimated individual component costs, which were incorporated into the total program cost, in section 4.3.5.

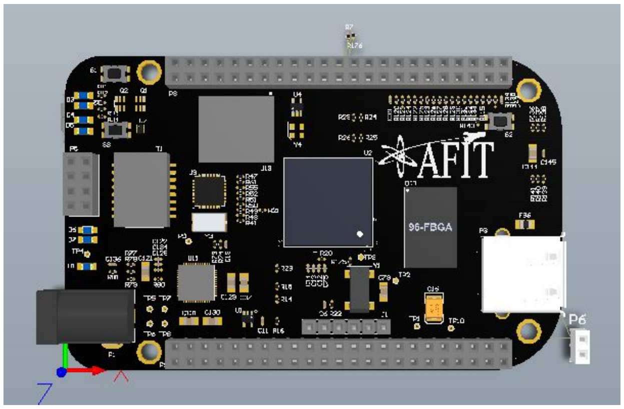

Figure 34 AFIT Beagle Bone Black [44]

4.3.5 Program Costs

Program costs were summed and given 30% margin for each subsystem in the WeatherSat, seen in Table 22. Without factoring in labor costs, the estimated cost per satellite is about $1.4M.

Table 22 Subsystem Cost Estimate for 1 Satellite [44]

Subsystem Cost of 1 Satellite	**% Allocated**	**Estimate ($K)**	**30% Margin**	**Total ($K)**
Payload	31.7%	340	102	442.0
Propulsion	12.1%	130	39	169.0
Structure & Mechanisms	2.3%	25	7.5	32.5
Thermal Control	0.0%	0	0	0.0
Power (incl. harness)	20.4%	218.5	65.55	284.1
TT&C	11.8%	126	37.8	163.8
On-Board Processing	0.2%	2	0.6	2.6
Software	6.9%	74.25	22.275	96.5
Attitude Determination & Control	14.6%	157	47.1	204.1
Total Cost ($K)	**100%**	**1072.75**	**321.825**	**1394.6**

Published launch costs and ground station costs from existing MC3 sites were added in to develop a final program cost. The final program cost, seen in Table 23, for all 198 satellites to be placed in orbit is $750M. One note, the best launch choice of Pegasus breaks the $1M constraint for launch cost by almost 2 times, at $1.8M per satellite. The lower cost options were rejected because the WeatherSat design exceeded mass and delta-V requirements for constellation establishment. Pegasus was the next lowest cost option.

Table 23 Total Program Cost [44]

	Min	Max (30% margin)	Comments
Satellites	214.6	278.9	Cost of 200 Satellites
Launch	360.0	468.0	Cost of 33 Launches
Ground Stations (New Locations)	1.6	2.1	Extrapolated from cost of MC3 @ AFIT (4 new sites)
Ground Stations (Updating S-Band)	0.8	1.0	Estimate based on expert opinion for parts and labor
Total ($M)	**$577 M**	**$750 M**	

4.4 Phase 3 Results

The initial design does not meet all of the objectives set forth in the weather mission, shown in Table 24. All of the resolution requirements of the seven weather phenomena were met, with the exception of sea state, wind profiles, and ocean currents due to the unknown resolution of the GPS scatterometry. The unknown resolution is carried as a risk, but the resolution is assumed to be comparable to similar sensors on the two small satellite programs, UK-DMC and CYGNSS. The objectives for using the MC3 network, downlinking within 30 minutes, revisiting within 30 minutes, storing collected data, and staying with a standard U form factor have also been met. The failed mission requirement concerns the satellite and launch costs. The constraint of launch cost under $1M per satellite will not be met because Pegasus is the lowest cost option to build the 198 satellite constellation. The launch cost has been minimized for this mission. The cost per satellite is around $1.4M. The $500K constraint does not include payload and propulsion cost. The WeatherSat cost per satellite without payload and propulsion is estimated to be $783.6K, which is over the cost constraint by a 157%.

Table 24 Mission Requirements Passed or Failed [44]

Pass/ Marginal/ Fail	Requirement	Description
P	Cloud Detection	The system shall detect and locate clouds to within 10 km
P	Lighting Detection	The system shall detect and locate lightning to within 10 km
M	Sea State	The system shall detect and locate sea state to within 10 km
P	Precipitation	The system shall detect and locate precipitation to within 10 km
P	Temperature Mapping	The system shall detect and map temperatures to within 10 km
M	Wind/Ocean Currents	The system shall detect and locate wind/ocean currents to within 10 km
P	Ground Station	The system shall use the MC3 University Network
P	Resolution	The system shall be comparable to state of the art systems
P	Rapid Download	They system shall be capable of downloading all data within 30 minutes of detection
P	World Wide Coverage	The system shall have < 30 minutes revisit rate at any location in the world (threshold), or continuous coverage (objective)
P	Data Storage	They system shall be capable of storing all collected data between downlinks
P	Form Factor	The satellite shall conform to standard “U” form factor
F	Satellite Cost	The satellite bus (not including payload or propulsion) shall cost less than $500K per satellite
F	Launch Cost	The launch system shall cost less than $1M per satellite

A major reason for exploring the capabilities of a CubeSat constellation to do the mission of current large and costly satellites is the cost benefit. This research showed that the cost per satellite could did not meet the expectations of $500K, but the WeatherSat program cost is about 21%[8] of the program cost for state-of-the-art weather satellites, such as the GOES series [70]. Yet this large cost benefit may not be realized when there are design risks that still need to be mitigated. Possible mitigation strategies will be discussed for the risks of GPS scatterometry resolution and LWIR radiometer low TRL as a precursor for further research.

4.4.1 Risk Mitigation Strategies

Risks include the TRLs of each selected instrument. As long as the constraints were met, the components were selected based on the highest TRL. The components are above a 6, with the exception of the FLIR Tau 2 640 at TRL 4, shown in Table 25. This risk can be mitigated through a risk control strategy of space-rated testing of the component or use on a research satellite to raise its TRL to at least a 6 for relevancy in the space environment. The radiometer may need significant development, to include: thermal management, radiation hardening, and validating the construction methods for vacuum so there are no trapped air pockets.

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[8] GOES series program costs are estimated at $10.9B [70] for the launch and operations of 4 satellites over 10 years. The WeatherSat comparison uses 3 rounds of launches for entire constellation replacement and $7.71M per year of operational cost for a total of $2.3B estimation.

Table 25 Component Technology Readiness Level

Sensor Component	TRL*	Reference
Malin Space Science Systems ECAM Optic	8	To be launched in September 2016 on OSIRIS-Rex [60].
FLIR Tau 2 640	4	Not validated in relevant environment.
MiRaTA passive MW radiometer	6	Predecessor, MicroMAS, was demonstrated in space [71].
Surrey Satellite Technology SGR-05U Receiver	8	Flown on 5 satellites [56], and similar Surrey GPS receivers integrated into operational satellites (UK-DMC) [67] and new programs (CYGNSS) [68].

* TRL chosen through chart [72] based on referenced system milestones.

The unknown resolution for scatterometry using a GPS receiver is a risk that should also be mitigated. There are a couple strategies that can be employed to address the unknown resolution. One strategy is to avoid the risk altogether by replacing the GPS receiver with a different sensor type of known resolution. A second mitigation plan is to control the risk through an alternative design by customizing the GPS receiver for this mission and/or separating the payload sensor suite into two satellite constellations to ensure the resolution requirement of 39.5 km is met.

The first strategy is to avoid this risk altogether by replacing the GPS receiver with a pair of passive microwave radiometers. The pair of radiometers was rejected during the payload sensor suite considerations due to the need for two radiometers to achieve polarized measurements versus one GPS receiver for scatterometry. Now that the GPS scatterometry resolution is potentially posing a problem, the pair of passive microwave radiometers can be considered once more. A quick analysis of swapping the sensors shows that this sensor trade will not cause the payload sensor suite to go over the technical budgets, seen in Table 26. The cost of this mitigation plan is an additional cost per satellite of about $249K, which is about $49.8M more for total program cost.

Table 26 Swap of GPS Receiver and Microwave Radiometer

Configuration	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 10.8 kg	< 5.4 U	< 12 W	< 75 kbps	Varies	Not limiting	Not specified
Old Configuration	1.63 kg	2.57 U	7.7 W	68 kbps	1 km through UNK	-20 C to 40 C (survival: No info)	Est. $340K
New Configuration	2.43 kg	4.29 U	9.9 W	71.5 kbps	1 km through 10 km	-20 C to 40 C (survival: No info)	Est. $589K

The second strategy is to mitigate the GPS scatterometry resolution risk by controlling the risk through an alternative design. One idea for an alternate design is to narrow the angle of view (AOV) on the antenna with a customized cone reflector to meet the resolution needed. Using Equation (1.3) for finding ground sample distance (GSD) from sensor AOV, the resulting AOV needed to meet 39.5 km resolution at 800 km is 2.83 degrees. This restricted AOV (RAOV) GPS receiver would not allow for worldwide coverage of the Earth because the WeatherSat constellation has been designed for a payload suite of no less than 60 degrees AOV [41]. The RAOV GPS receiver needs to be separated onto a second satellite and placed in a constellation scheme of a lower altitude. Table 27 shows that placing the RAOV GPS receiver at the low altitude of 400 km brings the AOV necessary to only 5.65 degrees.

Table 27 Trade of Altitude Vs. Angle of View

Altitude (km)	**GSD (km)**	**AOV (deg)**
800	39.5	2.83
400	39.5	5.65

Systems Tool Kit (STK) was used to simulate coverage of a second constellation of RAOV GPS receivers at 400 km with a similar Walker constellation scheme to the

WeatherSat: 85 degrees inclination, 11 planes, and 16 satellites per plane**.** Figure 35 shows that the constellation will not meet the 30 minute revisit time mission requirement, as the RAOV GPS receiver constellation only covers a fraction of the Earth's surface after 30 minutes. If the mission requirement could be changed based on the Department of Defense (DoD) oceanographic collection requirement of no less than a 6 hour revisit rate for wind and ocean measurements, the new RAOV GPS receiver constellation would suffice [73]. Figure 36 shows that this constellation could nearly achieve worldwide coverage in 3.25 hours.

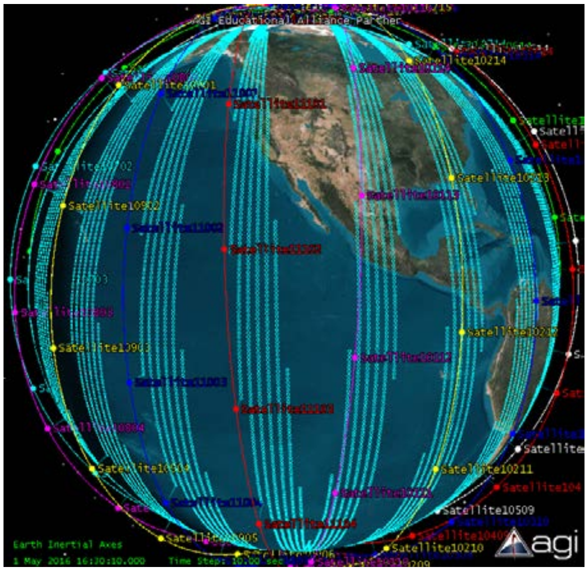

Figure 35 Restricted AOV GPS Receiver Simulation - 30 Minutes

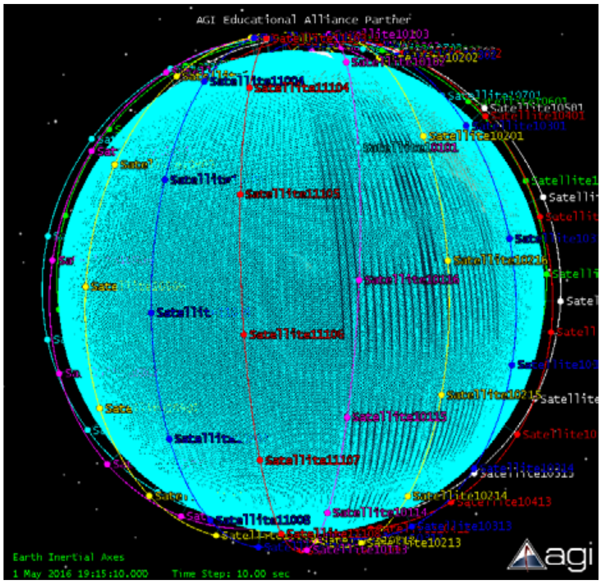

Figure 36 Restricted AOV GPS Receiver Simulation - 3.25 Hours

The team decided to choose a crosslink design instead of adding up to 7 new ground stations. So to optimize this second constellation, the distance between satellites in a plane cannot be more than 3000 km [41]. With only the GPS receiver separated out, the initial WeatherSat design will not change because the GPS receiver only affected 0.5% of the satellite mass, 0.7% of the volume, and 2.5% of the power consumption. Therefore, the cost of ensuring the GPS scatterometry met the resolution requirement of 39.5 km is the cost of building and launching a second satellite constellation and the customization costs of adding a cone reflector. The estimated cost of customizing a GPS antenna should be less than $15K , based on the research done in another thesis [74]. There is a concern that splitting the payload suite into two satellite constellations may diminish the quality of data collected once it is combined to deliver a weather prediction. The separated sensors will not allow ground processing to compare data from multiple wavelengths for the same location and time.

If a couple more sensors are separated into a second satellite design with the RAOV GPS receiver, those couple sensors will have to have an AOV similar to the receiver to avoid overdesigning. This scenario reduces the size of the original WeatherSat, and calls for a redesign of the entire system to find an optimum design. There will be cost benefits from lessened constraints of the two individual designs, yet the cost of launching and ground operates for a second constellation may cancel out those benefits.

4.4.2 Final Design

Comparing the outcomes of the risk mitigation strategies, the plan that requires the least re-design and the least increase to the total program cost is to replace the GPS receiver with a second passive microwave radiometer. The WeatherSat bus design and constellation scheme are left unchanged. Only the placement of payload sensors, depicted in Figure 37, is altered for the final WeatherSat design. The payload is within the constraints set by the technical budget, seen in Table 28, and is estimated to cost $765.7K per sensor suite (30% margin).

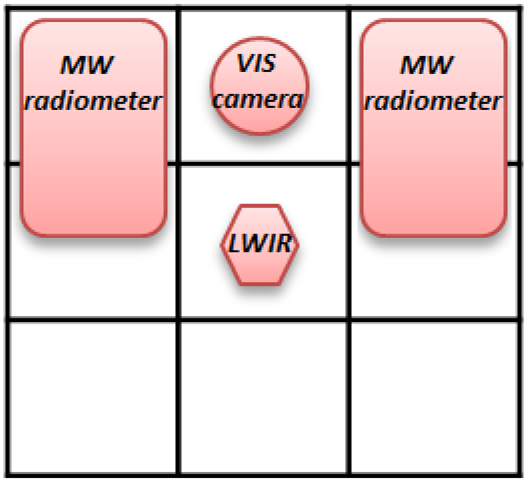

Figure 37 Final Payload Configuration (nadir-facing)

Table 28 Final Payload Sensor Suite

Name of Component	**Mass (kg)**	**Volume (U)**	**Average Power (W)**	**Data Rate (kbps)**	**GSD (km)**	**Temp Range**	**Cost**
Requirements	< 10.8 kg	< 5.4 U	< 12 W	< 75 kbps	< 6.5 km	Not limiting	Not specified [8]
VIS (Malin Space Science Systems ECAM-C30 WFOV [59], [60])	0.346 kg	0.51 U	2.5 W	28 kbps	1 km	-20 C to 40 C (survival: No info)	No info (est. $4.2K)
LWIR (FLIR TAU 2 640 w/ 7.5mm lens [50])	~ 0.15 kg	0.1 U	0.6 W	32 kbps	1.5 km	-40 C to 80 C (survival: -55 to 95 C)	$8.2K
2 MWR (MiRaTA [64])	1.82 kg	3.6 U	6 W	10 kbps	10 km	-40 C to 60 C (survival: No info)	No info (est. $550K)
GPS (1 left for ADCS [56])	0.11 kg	0.08 U	0.8 W	1.5 kbps	N/A	-20 C to 50 C (survival: -30 to 60 C)	$26.3K
Totals	**2.43 kg**	**4.29 U**	**9.9 W**	**71.5 kbps**	**1 km – 10 km**	**-20 C to 40 C (survival: same)**	**Est. $589K**

The mission requirements to detect and measure all seven weather phenomena are met, and the design is considered a success. The final cost per satellite of the final

WeatherSat proposed design is $1.72 M from Table 29, with a program cost of $814.8 M, seen in Table 30.

Table 29 Final Subsystem Cost Estimate for 1 Satellite

Subsystem Cost of 1 Satellite	**% Allocated**	**Estimate ($K)**	**30% Margin**	**Total ($K)**
Payload	44.6%	589	176.7	765.7
Propulsion	9.8%	130	39	169.0
Structure & Mechanisms	1.9%	25	7.5	32.5
Thermal Control	0.0%	0	0	0.0
Power (incl. harness)	16.5%	218.5	65.55	284.1
TT&C	9.5%	126	37.8	163.8
On-Board Processing	0.2%	2	0.6	2.6
Software	5.6%	74.25	22.275	96.5
Attitude Determination & Control	11.9%	157	47.1	204.1
Total Cost ($K)	**100%**	**1321.75**	**396.525**	**1718.3**

Table 30 Final Total Program Cost

	Min	**Max (30% margin)**	**Comments**
Satellites	264.4	343.7	Cost of 200 Satellites
Launch	360.0	468.0	Cost of 33 Launches
Ground Stations (New Locations)	1.6	2.1	Extrapolated from cost of MC3 @ AFIT (4 new sites)
Ground Stations (Updating S-Band)	0.8	1.0	Estimate based on expert opinion for parts and labor
Total ($M)	**$626.8 M**	**$814.8 M**	

4.5 Summary

Although, the initial WeatherSat design could not detect and measure all of the weather phenomena of interest, the design refinement completed in this thesis allowed for a final WeatherSat design that does successfully meet the mission objective. The mission requirement left unmet is the launch and satellite cost, which is argued to be unrealistic and do not reflect the operational needs of the system. The intention of this thesis was to propose a CubeSat design that delivers tactical weather data comparable to state-of-the-art measurements at a discount, and this design met that challenge.

V. Conclusions and Recommendations

5.1 Chapter Overview

Chapter V is a summary of the efforts documented in this thesis and final conclusions of the hypothesis that aCubeSat based WeatherSat satellite design can meet the terrestrial weather data collection needs of the U.S. military timely and inexpensively.

5.2 Conclusions of Research

The preliminary WeatherSat design does not meet the full tactical weather data collection needs of the U.S. military, as it does not meet the resolution requirement for the weather phenomena of sea state, wind profiles, and ocean currents. However, a design refinement conducted to correct the resolution requirement gap shows that the requirement can be met with some modifications to the payload sensor suite.

As the initial design came to completion, the team recognized areas of the mission requirements that needed refining as they were more restrictive than necessary in order to meet the larger mission objectives to collect weather data at low cost yet comparable to state-of-the-art satellite performance. At the conclusion of Phase 2, the mission requirement not met by the preliminary WeatherSat constellation was the cost cap of $1M for launch of each satellite. This constraint should be negotiable as the overall cost of the constellation is $814.8M compared to the $10.9B of the upcoming GOES-R series [70]. Over the span of 10 years, the WeatherSat operational cost with replacements would be around $2.3B, at $7.71M yearly operational cost [74]. This is about 21% of the $10.9B GOES program for four satellites over a 10 year design life.

The proposed WeatherSat design can deliver tactical weather data cheaply and also quickly, from contract to launch. The proposed WeatherSat constellation also is more robust compared to current weather satellite constellations. When the current geostationary weather satellites have failures, there are entire regions of the world for which weather data is missing and cannot be covered again until replacements are launched. A single WeatherSat failure only affects the revisit rate at a single point in the constellation.

5.3 Significance of Research

The commander of Air Force Space Command said this year that the DMSP-19 weather satellite is “about dead” [75]. The DoD weather collection abilities are once again in jeopardy, and the Air Force has been “struggling to determine where they would receive comparable data” in the budget constrained environment they are asked to operate under. The research accomplished to deliver a CubeSat constellation can meet this weather data gap and at a fraction of the cost of state-of-the-art weather satellites. It is imperative that the DoD look to the advantage achieved by CubeSats for a better alternative to the current costly satellite options.

5.4 Recommendations for Future Research

The team attempted to design a CubeSat bus and constellation scheme without a set payload design, which resulted in an unsound design approach. The payload must meet the high priority mission requirements, so there should not be unnecessary constraints placed on the payload in order to accommodate lesser priority requirements in the other subsystems. In this research, the unnecessary constraints the team placed on the payload was the low volume and power trade space and setting a data rate to research crosslinking options. Therefore, this final proposed design is not optimized for the weather mission as potentially better sensor options were rejected. A more sound approach for designing a weather data collecting CubeSat constellation is to have the team design the payload first and then use the remaining trade space for designing the bus and constellation scheme. Also concerning constraints that were too restrictive, it is better to leave as much trade space as possible at first and then reduce the options over the design process. In this thesis, the option to use a second microwave radiometer for sea state measurements was mistakenly rejected because it merely seemed to be infeasible in complexity and size. This sensor option should have been kept for further analysis to discover if it truly could not meet requirements. The last lesson learned from this research concerns the repeatability of the design process. The team accomplished much of the research independently and with varying methodologies for their final results, which was not fully documented. It would have benefitted the final design to have the team follow a set methodology and consistently vet reasoning for results with the whole team to keep a clear vision on the priorities of the mission.

Future research should include analysis of the proposed risk mitigation strategies concerning the lack of information on what resolution the GPS scatterometry can measure and the low Technology Readiness Level (TRL) of the long wave infrared (LWIR) radiometer. In order to be a feasible alternative to state-of-the-art weather satellites, the WeatherSat design needs to offer capabilities that can reliably work in a space environment. The TRL should reflect confidence in space performance, so any components falling below a TRL 6 should undergo risk mitigation.

The uncertain performance of the GPS receiver for scatterometry measurements has led to multiple risk mitigation suggestions. It is recommended that further research be done across all of the suggested mitigation strategies to confidently conclude the best design to implement. These strategies include: 1) avoidance by replacing the GPS receiver with a second passive microwave radiometer, and 2) control by customizing the GPS receiver and separating it into a separate constellation, where the GPS receiver is the only sensor on the new satellite or more sensors accompany the receiver in a complete redesign of the initial WeatherSat.

A second, and arguably more profound, recommendation concerns the design choice of employing a crosslink to meet the downlink requirement of under 30 minutes from detection versus simply adding more ground stations. The team decided early on to research the possibility of crosslinking to meet this requirement. Yet through the thesis of a fellow researcher, it was discovered that adding ground stations proved to be the less costly option [74]. The crosslink added an additional constraint that the satellites needed to be nor more than 3000 km apart, resulting in a revisit time of 4 minutes and greatly exceeding the required 30 minute revisit time. It is suggested that the seven ground stations be built and future research optimizes a constellation design without the use of crosslinks.

The U.S. military is already seeking CubeSat solutions for their weather data needs, demonstrated in the Navy Small Business Technology Transfer (STTR) [9]. The objective of the STTR is to use CubeSats to measure maritime weather, including cloud characterization, sea surface winds and temperature, sea ice characterization, tropical cyclones, and overall theater weather imagery. This thesis may not have an optimized design to specifically measure these maritime weather phenomena, but it is recommended that the final WeatherSat design capabilities be shared as a possible design or further the research effort to design a CubeSat for the Naval mission requirements.

5.5 Summary

The outcome of this research is a proposed CubeSat design for collection and transmission of weather data. This work is the stepping stone to an executable constellation to perform the mission necessary for the DoD tactical planning. This thesis details a constellation that can improve data downlinking and dissemination of weather conditions to be effectively utilized by the U.S. military.

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14. ABSTRACT

This thesis investigates a CubeSat design that uses Commercial-Off-The-Shelf (COTS) components to capture, store, process, and downlink collected terrestrial weather data at resolutions near stat-of-the-art. The weather phenomena to be detected and transmitted in a timely manner are cloud formations, wind profiles, ocean currents, sea state, lightning, temperature profiles, and precipitation. It is hypothesized and shown that the proposed design will provide an improvement on the current U.S. tactical weather collection satellites because of the anticipated increased reliability and lowered cost to build and maintain the proposed CubeSat constellation. The methodology employed a multi-phase approach through the collective research of a team of Air Force Institute of Technology (AFIT) master’s students to develop an initial satellite and constellation scheme, with my contributions as the payload lead. This thesis documents the initial satellite design and, through my risk reduction effort to refine the payload, proposes a final payload configuration to meet tactical weather requirements. The final payload includes three types of sensors and is used in 198 identical CubeSats of a LEO Walker constellation. This research has the potential to increase the reliability of weather data collection for the military, while at a low cost.

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CubeSat, Visible Camera, Long Wave Infrared Radiometer, Passive Microwave Radiometer, Global Positioning System Scatterometry

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