Space Missions with SOKS

The First Complete Overview of Space Missions with Sub One Kilogram Spacecraft Launched in the Past (1957-2016)

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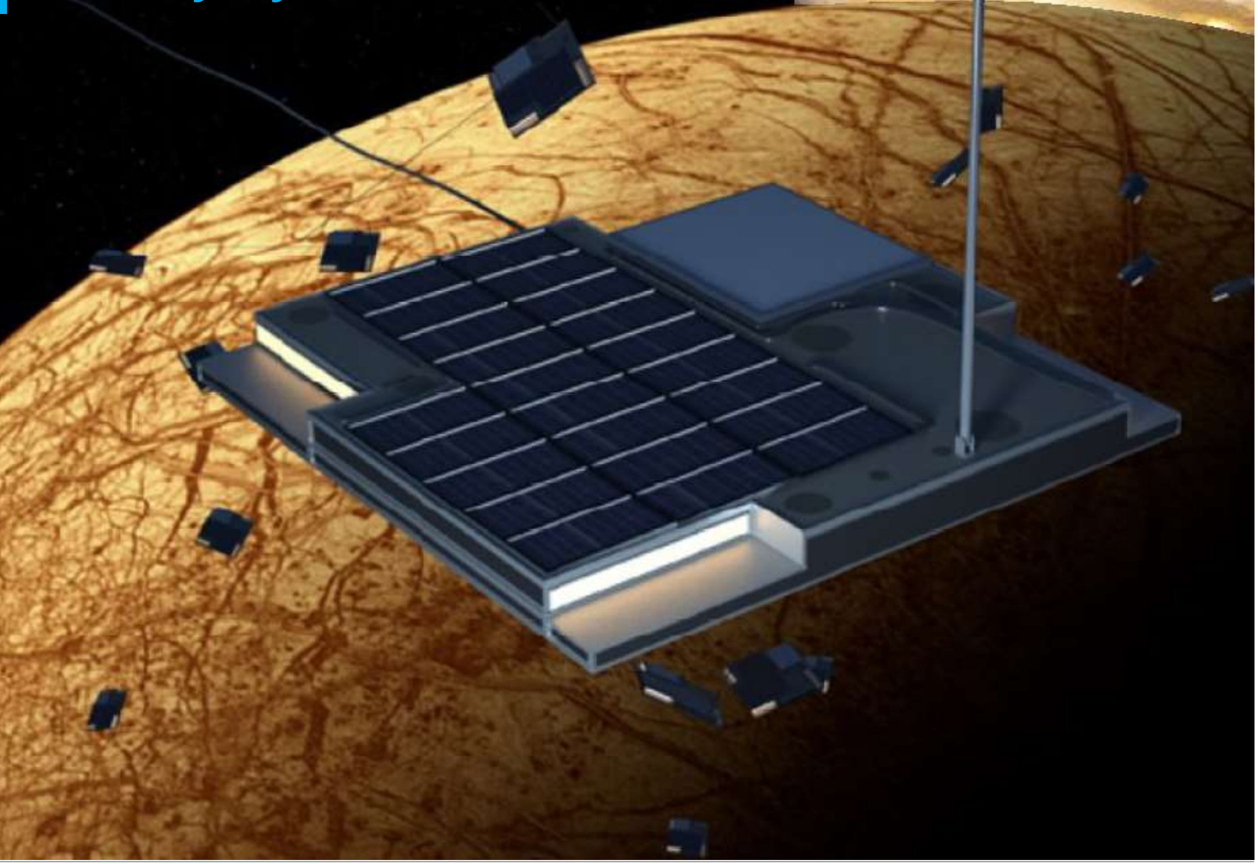

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Challenge the future

Space Missions with SOKS

The First Overview of Space Missions with Sub One Kilogram Spacecraft Launched in the Past (1957-2016)

By

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CONTENT

ABSTRACT

The success of CubeSat after 2005 resulted in bright future expectations of Spacecraft with a mass below one kilogram. Although these spacecraft are usually known as Pico and FemtoSat, their ambiguous nature and inconsistent use in literature resulted in the use of an alternative, namely Sub One Kilogram Spacecraft, or simply said SOKS. Slogans like 'Smaller, Cheaper, Faster' or 'Do More with Less' are easy to encounter in the proposed concepts of Space Missions with SOKS, as well as statements like 'Think Big, Fly Small' and 'The next big thing in Space is something small'. However, the expectations are only based on these concepts and are in contrast with the reality, which show a limited record of launches. What would the expectations be based on Space Missions with SOKS from the past? Would they foresee the same bright future or would they state the opposite?

The search for a scientific motivation of these expectations resulted in the first complete overview of Space Missions with SOKS that were launched in the past. This thesis provides a journey through time from the controversial West Ford Needles, at the start of the Space Age, to beyond the first crowd funded Space Missions known as KickSat 1. It also resulted in a unique dataset of Space Missions with SOKS. The analysis thereof provided new insights with a clear outcome. A selection of these graphical representation is presented and discussed in this report. This thesis provides the latest update regarding, for instance, the applications and success rates, as well as the countries that have their SOKS Missions throughout history. The end of this thesis addresses the expectations based on these results.

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ACRONYMS

A

AC1	Aerospace Corporation 1
AIM	Asteroid Impact Mission
AMSAT	Radio Amateur Satellite Corporation
ARM	Atmospheric Re-Entry Mission
ARS	Amateur Radio Satellite
ASIC	Application Specific Integrated Circuit

C

CB	Circuit Board
CC	Corner Cube
CCTV	Closed Circuit Television
CDMA	Code Division Multiple Access
COTS	Commercial of the Shelf
CRS	Commercial Resupply Services
CS	Calsphere
CS1	Calsphere 1
CS2	Calsphere 2
CS3	Calsphere 3
CS4	Calsphere 4
CS5	Calsphere 5

D

DARPA	Defense Advanced Research Projects Agency
DCE	Dual Calsphere Experiment
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense

E

ECC	Error Correction Code
ELaNa	Educational Launch of Nanosatellites
ELS	Extended Literature Study
EMW	Electromagnetic Wave
ERS	Environmental Research Satellite

F

FD	Flight Day
FM	Frequency Modulation

G

GPS	Global Position System
GDE	Gridsphere Drag Experiment
GDE1	Gridsphere Drag Experiment 1
GDE2	Gridsphere Drag Experiment 2
GUS	General Utility Spacecraft

H

HAM	Amateur Radio Operator
HANE	High Altitude Nuclear Explosions
HH	Hitchhiker

I

IC	Integrated Circuit
IDSS	Interconnected Distributed Space System
IGY	International Geophysical Year
ISS	International Space Station

J

JSC	Johnson Space Center

K

KS1	KickSat 1

L

LP	Lorentz Propelled

M

MB	Mylar Balloon
MB1	Mylar Balloon 1
MB2	Mylar Balloon 2
Mc	Mega Cycles per Second
MDA	Motorized Door Assembly
MII	Microscale Infinite Impulse
MIS8	MISSE-8 Sprite
MISSE-8	Materials International Space Station Experiment 8
MN	Mission Name
MSS	Millimeter-Scale Solar Sail

N

NA	North America
NASA	National Aeronautics and Space Administration
NAVSPASUR	Naval Space Surveillance System
NORAD	North American Air/Aerospace Defense
NRL	Naval Research Laboratory

O

OD	ODERACS
OD0	ODERACS 0
OD1	ODERACS 1
OD2	ODERACS 2
ODERACS	Orbital Debris Radar Calibration System
OPAL	Orbiting Picosatellite Automated Launcher
ORS	Octahedral Research Satellite
OSCAR	Orbiting Satellite Carrying Amateur Radio
OV	Orbiter Vehicle
OV1	Orbiting Vehicle 1

P

P-POD	Poly Picosatellite Orbital Deployer
PasComSat	Passive Communication Satellite
PCB	Printed Circuit Board
PCSA	Projected Cross Sectional Area
PCSC	Passive Communication Spacecraft
PRN	Pseudo Random Number
PST	Pacific Standard Time

R

RAE	Royal Aircraft/Aerospace Establishment
RCS	Radar Cross Section

S

SOKS	Sub One Kilogram Spacecraft
SPADATS	Space Detection and Tracking System
SRP	Solar Radiation Pressure
SSB	Space Science Branch
SSD	Solar Sail Disk
SSM	SOKS Space Mission
StenSat	Stenhouse Satellite
STP	Space Test Program
STS	Space Transportation System

T

TACS	Tethered Aerospace Corporation Spacecraft
TCE	Triple Calsphere Experiment
THEL	Artemis Thelma and Louise
TRS	Tetrahedral Research Satellite
TRW	Thompson Ramo Wooldridge

U

US	United States
USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
UTC	Coordinated Universal Time
UV	Ultra Violet

W

WF1	West Ford 1
WF2	West Ford 2

NOMENCLATURE

A

Active Communication Spacecraft
Spacecraft that are used for communication purposes by receiving and transmitting (modulated and or amplified) electromagnetic waves.

Active Tracking
Tracking using a Tracking Signal.

Amateur Radio
Non-commercial communication through electromagnetic waves that have a frequency that falls within the allocated frequency for Radio Amateurs.

Amateur Radio Satellite
Spacecraft that are built and used by Radio Amateurs.

Artificial
Made by humans, manmade.

Atmospheric Drag
The force exerted on a body in the opposite way of the direction of movement due to the atmosphere.

B

Backer
A sponsor that donates money to a project through Kickstarter.

Balloon Spacecraft
Spacecraft that is inflated in orbit in the form of a sphere.

C

Charge Drag
The force exerted on a body by electrical charging and or discharging due to the plasma surrounding.

Code Division Multiple Access
The division of unique codes to multiple communication devices in order to establish simultaneously communication links on the same operating frequency.

Communication System
The components on the spacecraft that are solely used for the establishment of a Communication Link.

Congruent Spacecraft
Spacecraft that have or are assumed to have the same form and size.

CubeSat
A Spacecraft the size of a One Unit (1U) CubeSat, or a multiple or fraction thereof

D

Deployment System
The components of a spacecraft that are solely used for the deployment of another spacecraft, or the spacecraft itself, into orbit.

Dipole Belt
Artificial belt around the Earth that consists of Dipole Needles.

Dipole Clusters
Clusters of Dipole Needles.

Dipole Needle
Hair like wire with a length half the wavelength of the electromagnetic wave at which it resonates.

Dispensing
The operation of expelling individual Dipole Needles from the Needle Dispenser.

Dispersion
The process by which the formed Dipole Belt becomes gradually more diffuse.

Distributed Space System
The use of multiple Spacecraft in Space as one system.

Downlink
Return link that is established from a spacecraft to a ground segment on Earth.

Dragsphere
A spherical spacecraft placed in orbit of which it is assumed that the main perturbation consists only of the atmospheric drag.

E

Ejection
The separation of the piggyback from the main payload.

F

Film
A thin sheet of Plastic.

Foil
A thin sheet of Metal.

Forward Error Correction
The checking and correcting (to a certain extend) of Telemetry through the Error Correction Code by the receiver without the use of a retransmission of the same Telemetry.

G

General Utility Spacecraft
Congruent spacecraft with a payload that can differ from spacecraft to spacecraft and is supported by a set of slightly customizable and or modifiable standardized subsystems that is assumed to be more or less the same for each spacecraft.

Gold Codes
A deterministic algorithm.

Gridsphere
Balloon spacecraft with a grid surface made out of pentagonal and hexagonal wires that are enclosed by photolyzable film.

Gridsphere Drag Experiment 1
Gridsphere Drag Experiment launched in 1968.

Gridsphere Drag Experiment 2
Gridsphere Drag Experiment launched in 1971.

H

Household Data
The measured parameters on the spacecraft that do not belong to the payload data but is still transmitted by the communication system of the spacecraft.

I

IGY Minitrack
The initial Minitrack that was set up as part of the International Geophysical Year.

Injection
The placing of the fairing into orbit by the launch vehicle.

Insolation
The total amount of solar radiation energy received on a given surface area during a given time.

M

Matched Filtering
The filtering of electromagnetic waves by a receiver based on a certain correlation.

Mesh Dimensions
Dimensions of the shapes that forms a grid.

Metalized Film
A film covered with foil.

Mylar Balloon
Balloon Spacecraft that is made out of Aluminized Mylar.

Mylar Balloon 1
Mylar Balloon used for the Gridsphere Drag Experiment 1.

Mylar Balloon 2
Mylar Balloon used for the Gridsphere Drag Experiment 2.

N

Non-Keplerian Orbit
An orbit in space where the three orbital laws of Kepler do not apply.

O

OD0-C
Polished 2 inch ODERACS 0 Spacecraft.

OD0-D
Sand Blasted 2 inch ODERACS 0 Spacecraft.

OD0 GAS Canister
The 5 [ft3] GAS Canister with MDA that is used for the ODERACS Mission in 1992.

OD1-C
Polished 2 inch ODERACS 1 Spacecraft.

OD1-D
Sand Blasted 2 inch ODERACS 1 Spacecraft.

OD2-D
Polished 2 inch ODERACS 2 Spacecraft.

ODERACS 0
The ODERACS Mission launched in 1992.

ODERACS 1
The ODERACS Mission launched in 1994.

ODERACS 2
The ODERACS Mission launched in 1995.

Onboard Data Handling System
The components on the spacecraft that are solely used to receive, process and if needed temporarily store Telemetry and or Telecommands onboard the spacecraft before they are send to the right subsystems and or the payload.

Orbit Control System
The components of a spacecraft that are solely used to determine and correct or change the movement of the spacecraft.

Orbital Dynamics
The study of Orbital Elements of Spacecraft.

P

P-POD
CubeSat Deployer.

Passive Communication Spacecraft
Spacecraft that are used for communication purposes by reflecting electromagnetic waves.

Passive Tracking
Tracking without the use of a Tracking Signal.

Photolyzable Film
Thin sheet of plastic that dissolves once it is exposed to Ultra Violet Waves.

Pinging
Make a Spacecraft transmit a beeping sound on command.

Power System
The components of the spacecraft that are solely used to provide the required power to the payload as well as the other subsystems.

Projected Cross Sectional Area
The shape of the detected object that is seen with respect to the radar.

Proof of Concept
The validation of a concept in space that is not proven yet.

Pseudo Random Noise
A binary sequence that is obtained through a deterministic algorithm and looks like random noise when it is included in transmitted electromagnetic waves.

R

RADAR
A system that uses Radio Waves for detection and ranging purposes.

Radar
A system that uses electromagnetic waves for detection and ranging purposes.

Radar Cross Section
A measure of the ability of an object to reflect the transmitted Electromagnetic waves of a Radar in the direction of the receiver of the radar.

Radio Amateur
Amateur radio operator.

Repeater
A device that receives Electromagnetic waves with a certain frequency and transmits it again on the same or another frequency.

Resonant Orbit
Earth Orbit where the perigee altitude decreases over time due to solar radiation pressure of the Sun.

Return Link
One-way communication link that is used solely to transmit Telemetry.

S

Satellite
A natural or artificial (manmade) orbiting body.

Satelloon
Balloon Spacecraft.

Smart Dust
Concept of a miniaturized self-contained sensor.

Solar Radiation Pressure
The force exerted on a body by Electromagnetic waves coming from the Sun.

Space Debris
All the natural orbiting objects and non-functioning artificial orbital objects that serve no function and form a threat to other functional spacecraft in space.

Space Dust
Dust sized objects in space.

Space Proven Hardware
Hardware that is successfully used in Space.

Space Shuttle
A launch vehicle that consists of two Solid Rocket Boosters, an External Tank and an Orbiter Vehicle.

Space Surveillance
The detection, tracking and cataloging of natural as well as artificial objects in space and the monitoring of activities in space.

Space Surveillance Network
A network of Space Surveillance Systems.

Spacecraft
An artificial (manmade) object that is designed for the space outside the atmosphere of the Earth.

Stainless Steel
Iron Alloy.

Standard Target
An object that is placed in an orbit in space for calibration purposes.

Standardized Subsystem
Spacecraft subsystem that is designed to be used for a range of spacecraft that can support a range of payloads.

Structure System
The components of the spacecraft that are solely used to provide structural and or mechanical support to the payload and the remaining subsystems that support the payload.

T

Technology Demonstration
The testing of Hardware in space that is not Space Proven yet.

Telemetry
The measured data by a System at a remote distance.

Thermal Control System
The components of a spacecraft that are solely used to determine and influence or control the temperature of the spacecraft.

Tracking
Determining the position of a spacecraft in space and time with an Earth based station.

Tracking Beacon
A transmitter installed on a Spacecraft that operates at the same frequency as the receivers of the IGY Minitrack Network.

Tracking Signal
Electromagnetic waves that are transmitted for tracking.

TRS I
The General Utility Spacecraft that belongs to the TRS Mark I family.

Twin Spacecraft
Spacecraft that are assumed to be identical.

U

Upper Atmosphere
The atmosphere of the Earth that lies between the altitude of 20 to 100 km.

Upper Atmosphere Pollution
The situation where a spacecraft causes a harmful effect on the upper atmosphere during re-entry.

W

West Ford 1 Needle
The Dipole Needle used for West Ford 1.

West Ford 1 Needle Dispenser
Needle Dispenser used for West Ford 1.

Wire
A thin flexible thread of metal.

1

THE OUTLINE OF THE THESIS

Abstract – The thesis is outlined in this chapter through three sections. The background section provides the aspects and motivations that led to this thesis. The subsequent section starts with an explanation why the new type of Spacecraft, referred to as Sub One Kilogram Spacecraft or simply said SOKS, is defined. Thereafter, the research statement is stated, based on the background information. In addition to that, the research questions for this thesis are discussed and defined, based on the research statement. Subsequently, the applied methodology for this thesis is discussed. The third section contains the outline of the report, which is a result of the defined thesis that is discussed in the second section.

1.1 BACKGROUND

Intro – The beginning of the Space Age started with the successful launch of Sputnik 1 in 1957. Numerous Spacecraft, that vary in size and mass, have been launched since then. They were developed by various countries, either in collaboration or on their own, and were launched from all sorts of places. They were furthermore used for a diversity of applications, and were placed in a variety of orbits. These characteristics, among other ones, have each been used to categorize different types of Spacecraft. One of these categorizations was, for instance, based on the mass of the Spacecraft. The names of these type of Spacecraft vary nowadays usually from Large Satellite to Femto Satellite. Each of these Spacecraft types have their own launch history. Some of them have been launched for more than half a century, while others have just been launched for one or two decades. The latter has been the case for Nano and Pico Satellite (cf. Figure 1). Both Spacecraft types experienced, after 2005, a gradual increase of annual launches. By the end of 2013, there was even a substantial increase in comparison to the years before. These developments were a result of a launch in 2003 that contained several CubeSat. A **CubeSat** is a Spacecraft the size of a One Unit (**1U**) CubeSat, or a multiple or fraction thereof. Back then, a **1U CubeSat** was defined as a ten centimeter cube spacecraft with a mass below one kilogram. A three unit (**3U**) CubeSat, which is the size of three 1U CubeSat, was, next to multiple 1U CubeSat, also launched in 2003. Although it did not have the shape of a cube, it was still referred to as CubeSat since it was a multiple of a 1U CubeSat. The mass restrictions of the bigger sized CubeSat increases by the number of their 1U CubeSat multiples. The mass of CubeSat could therefore be just below one or just above one kilogram. They were therefore also referred to as Nano and Pico Satellite, or Nano and **PicoSat**. The success of the CubeSat in the years thereafter triggered the expectations of Femto Satellite, or simply said **FemtoSat**. It seemed just a matter of time before they would be launched too.

Prior Research – The topic of the Literature Review, that was done prior to this thesis, was therefore set to this type of spacecraft. The lack of actual space missions with FemtoSat resulted in a Literature Review of the published Spacecraft and Mission Concepts. A minority of these concepts was published around the millennium and in some years thereafter. The majority, however, was published after 2006. This distribution made the expectation for FemtoSat seem more justifiable due to a resemblance in distribution with the annual launch rates of Nano and PicoSat (cf.

Figure 1). In addition, the review showed that the mission concepts ranged from Earth based missions to Interstellar Missions where the FemtoSat were used for a variety of applications. The applications ranged from inspecting the spacecraft that carried the FemtoSat, to sampling a planetary atmosphere with a numerous amount of FemtoSat. The limited capabilities of a such a spacecraft would be compensated through the use of multiple FemtoSat that act together as one. This would provide new possibilities for space missions that could not be done with bigger sized spacecraft. Vice versa, they would be able to do the same kind of missions as that of bigger sized spacecraft. In addition, the idea was to make use of small, cheap and simple FemtoSat that were easy and fast to design, integrate, and produce, even on large scales. This would be possible through the use of commercially available mass produced miniaturized components that were easy to customize and integrate with components of the same kind. Slogans like '*Smaller, Cheaper, Faster*' or '*Do More with Less*' were therefore often encountered during the literature review. Other promising statements for FemtoSat were '*Think Big, Fly Small*', and '*The next big thing in Space is something small*'.

Issues – Despite the bright future prospects and possibilities for FemtoSat, there were some issues that made these statements less convincing or questionable. One of them was for instance the contrast between what was stated and the reality. If FemtoSat had so many benefits, then why were not already used for recent Space Missions? After all, for some of the concepts, the required technology was already available since the start of the Millennium. An explanation could be another issue that was observed, namely the applied methodology for the conceptual design, in particular, that of the spacecraft. Due to the lack of FemtoSat launches, other conceptual design methodologies were used, like the ones for Medium and Large Satellite. A PicoSat on the other hand, the closest to a FemtoSat in terms of mass, did have a launch history. Why were these spacecraft not used for the conceptual design? One of the answers seemed to be conflicting literature and the inconsistent use of the definition of PicoSat. Apparently, PicoSat seemed to be also waiting for their great success. The ones that were launched (cf. Figure 1), especially after 2008, seemed to be actually NanoSat. The initial expectation, that it would be a matter of time before FemtoSat would be launched

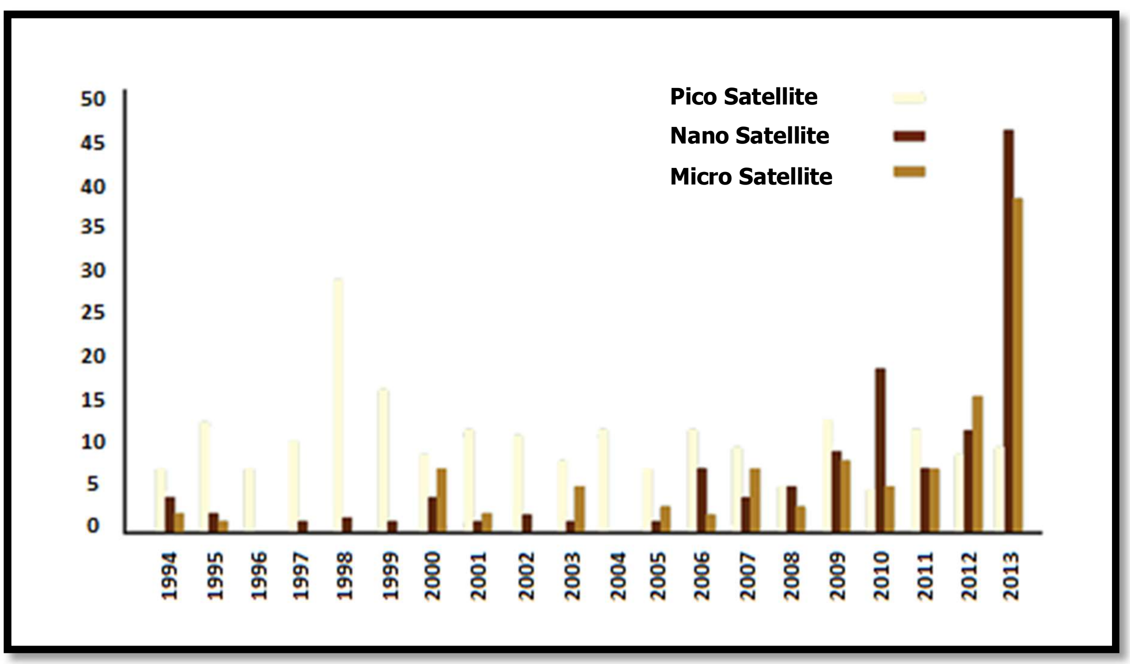

Figure 1: The annual launches of Micro, Nano, and Pico Satellite from 1994 up to 2013. The mass limitations for these Spacecraft are respectively below 10 [kg] up to 1 [kg], from 1 [kg] up to 100 [g], and below 100 [g]. [1]

too, was therefore extended to PicoSat. In other words, Spacecraft with a mass below one kilogram were expected to be next.

1.2 THE THESIS

SOKS – Spacecraft with a mass less than one kilogram are occasionally referred to as Small Satellite, Very Small Satellite, Ultra Small Satellite, or Miniaturized Satellite (cf. Table 1). All these names use words that are not quantifiable and are therefore ambiguous by nature. Some of them are also confusing due to varying definitions in literature. A Small Satellite, for instance, is also used to denote Spacecraft with a mass below 500 kilogram or a mass between 500 to 100 kilogram. The alternative, Pico and FemtoSat, is sometimes also used to denote Spacecraft with a mass below one kilogram. In these cases, a FemtoSat is, by definition, a spacecraft with a mass below 100 grams, since PicoSat are consistently defined as Spacecraft with a mass between one kilogram and 100 grams. Nevertheless, FemtoSat are also defined as spacecraft with a mass between 100 grams to 10 grams. In that case, although uncommon, Atto and Zepto Satellite are used to refer to spacecraft with a mass of, respectively ten to one gram and ten to one milligram. Using FemtoSat, in Pico and FemtoSat, is therefore also confusing because of the alternative definition as well as the additional defined Spacecraft Type that might come along. Although PicoSat is consistently defined in literature, the association to CubeSat results in an unclear definition, especially since the mass limitation of a 1U CubeSat is set to 1,3 Kilogram. A 1U CubeSat is actually also not a cube but a cube shaped spacecraft because of the deployment rails. It is therefore also possible to define a 1U CubeSat based on its outer dimensions, instead of the design volume. Similar stories apply to the prefixes Pico and Femto. They are usually associated as a multiplication factor to decrease the number of figures (in other words, digits) of a value with a metric unit, like gram or meter. The prefix **Pico**, for instance, is a multiplication factor of one times ten to the power of minus twelve (1E-12). A picogram is thus a trillionth of a gram, nevertheless, a PicoSat is a Spacecraft with a mass between one kilogram and 100 grams. The common known definitions of the prefixes are not preserved for the categorization of spacecraft by their mass. They are therefore considered in this case also unclear since the prefixes suggest a different mass range for the Spacecraft mass. The afore mentioned ways to refer to Spacecraft with a mass less than one kilogram are, thus, either ambiguous, unclear, inconsistent, or a combination therefore. This resulted in a preference to use an annotation that is clear and concise, especially regarding mass range of the spacecraft. The annotation that fulfilled these preferences seemed to be **Sub One Kilogram Spacecraft**. The name explains itself already. It clearly indicates that Spacecraft with a mass less than one kilogram are considered under this name. Although the abbreviation **SOKS** does not fulfill these preferences, it does sound catchy and is easy to use, pronounce and remember. The naming is also convenient for future use since there is room for variations, like Sub One Gram Spacecraft, or just **SOGS**. In addition, the association to actual socks might provide the opportunity to draw attention whenever needed. An example of this is for instance a news article with a title like '*TUDelft Students launched SOKS in Space*". The main disadvantage of using Sub One Kilogram Spacecraft and SOKS is that it is not commonly used yet. Nevertheless, it did not outweigh the aforementioned conflicts and therefore also not the use thereof. Spacecraft with a mass less than one kilogram are therefore referred from here on as **Sub One Kilogram Spacecraft**, or simply said **SOKS**. For convenience, a launched Space Mission with SOKS is referred to as SOKS Space Mission or **SSM**. Both definitions came along with some exceptions.

Exclusions – In 2009, the mass restriction for 1U CubeSat was relaxed with a third of a kilogram. Since then, it has been possible to use both categorizations for 1U CubeSat. However, it is difficult to determine which 1U CubeSat is a PicoSat and which one a NanoSat. The mass of CubeSat is often annotated by the size of the CubeSat. In case a specific value is given, it is often rounded off to one or one point three kilogram. Based on the increase of the mass limitation of 1U CubeSat, it is assumed that the mass of one kilogram was not enough and that the 1U CubeSat, after the mass revision, contained most likely a mass more than one kilogram. In other words, they are considered to be NanoSat. In addition, already more than 400 CubeSat were launched so far. With this amount of launched Spacecraft, it seems better to considered them as a class on their own. 1U CubeSat or bigger sized CubeSat, with a mass less than one kilogram, are therefore not considered to be SOKS and therefore also not SSMs.

Table 1: A selection of different Spacecraft Types in literature, based on the Spacecraft Mass. The prefix is placed before, and or merged with, either Satellite or Spacecraft. A Sub One Kilogram Spacecraft represents in this case Pico, Femto, Atto and Zepto Satellite.

	Spacecraft Mass			Category
	Min	**Max**	**Unit**	**Prefix**
	1000	-	[kg]	Large
	500	1000	[kg]	Medium
	100	500	[kg]	Small
	10	100	[kg]	Micro
	1	10	[kg]	Nano
S	0.1	1	[kg]	Pico
O	10	100	[g]	Femto
K	1	10	[g]	Atto
S	0.1	1	[g]	Zepto

Statement – The expectation that SSMs would be the next big thing in space, together with the identified issues that made this statement less convincing, was the reason to dedicate this thesis to SOKS. What would the outcome of the expectation be in case it was based on SSMs that were launched in the past? The answer to this question would solve some of the issues that were observed during the prior research. It would be possible to compare, for instance, the applications of the published concepts with the applications from the past. This comparison could provide a better perspective on the current capabilities of SSMs and it could result in less contrast between the expectations and the possibilities. In addition, it would also be clear whether it would possible to derive conceptual design relations from SSMs from the past. If so, then it would be possible to validate the conceptual design of SSMs that were based on bigger sized Spacecraft and adjust the possibilities where needed. Last but not least, it would provide the possibility to outline future plans of SSMs based on scientific motivations. The afore mentioned arguments resulted therefore in the following research statement.

Research Statement

The Space Missions with Sub One Kilogram Spacecraft that were launched in the past might rule out whether the next big thing in space would be Sub One Kilogram Spacecraft.

Questions – The limited and conflicting literature about SSMs did not provide a conclusive view of the SSMs that were launched in the past. It is therefore of importance to determine first what SSMs were actually launched in the past. For the prediction based on the past, it is important to determine, for instance, why the SSMs were launched in the first place, what they were used for, and why the SSMs worked out or not. In other words, the next step is to determine all the mission characteristics, starting from the needs that resulted in the SSMs, to the results of the SSMs. By compiling the characteristics of each SSM, it is possible to obtain new insights through an analysis of this compilation. The insight might contain also information regarding the course of SSMs in the future. These views resulted therefore in the following research questions.

First Research Questions

What are all the space missions, in the literature within disposal, that can be categorized, despite conflicting literature, as 'Space Missions with Sub One Kilogram Spacecraft that were launched in the past between 1957 to 2016', after, first defining and then, applying a systematic literature study that can overcome the conflicting literature issue.

Second Research Questions

What are the details of the mission characteristics, in particular that of the, launch date, country, status, and application, for each of the identified Space Missions with Sub One Kilogram Spacecraft, that were obtained through the applied literature study?

Third Research Questions

Does a graphical overview the obtained mission characteristics, over the period between 1957 to 2016, provide an observable trend or insight that can be used to address the research statement?

Methodology – For the first two research questions a literature study is required. As was mentioned before, during the literature review, it was noticed that the literature about the concepts of SOKS, SSM Concepts, as well as the launched SSMs, was limited, inconclusive, and conflicting with one another. In order to provide a conclusive answer to the research statement, this issue needed to be resolved first, else the outcome of the thesis would be depended on the literature that was selected. A systematic approach for the literature study was therefore defined in an attempt to resolve these issues. For convenience, this approach is referred to as the **Extended Literature Study** (**ELS**). The idea is to obtain, with the resources at disposal, all the relevant literature that is within reach. After the collection of the literature, all the literature is processed and the relevant information is extracted and compared with one another. By comparing the given information as well as the type of reference, it should be possible to determine what literature to consider and what not. Although these steps are clear, it is of importance to evaluate already during the Literature Study if ELS provides the desired result. ELS is therefore applied first to one SSM. The improved version is thereafter used for the next SSM. There were already seven SSMs identified during the Literature Review, prior to the thesis. There are therefore seven iterations possible for the Literature Study. This is more than enough to obtain the desired result through ELS. It therefore expected that the Extended Literature Study will result eventually in a dataset that could provide, thus, a conclusive answer to the remaining research question and therefore also the research statement.

1.3 REPORT OUTLINE

Intro – The remaining body of the report is a result of the applied research methodology to obtain the answers to the research questions and address the research statement. It consists of thirteen more chapters that are spread over three sections. The first section is a result of the literature study that was required to answer the first and second research questions. The second section provides the analysis and discussion of the dataset, that was obtained through the literature study, in order to answer the third research question. The last section concludes the outcome of the research questions, based on Section I and Section II, and addresses the research statement based on these conclusions. Throughout these sections, a bold word, or set of bold words, is placed at the beginning of each paragraph to provide an indication of the discussed topic. The detailed overview of each section is provided in the following paragraphs.

Section I – The Space Missions with Sub One Kilogram that were launched between 1957 to 2016 are discussed at length in Section I. This section contains in total eight chapters. The first seven chapters of this section, Chapter 2 to Chapter 8, discuss each a set of SSMs that were related to one another. The chapters are furthermore chronologically ordered in time, and are obtained through the Extended Literature Study. The last chapter of this section, Chapter 9, provides a brief overview of the SSMs that were launched just before, and after the start of this thesis. This chapter is added for completion and is not obtained through ELS.

Section II – The combined set of characteristics of each SSM, provided in Section I, are analyzed and discussed in Section II. This section contains in total four chapters. In Chapter 10, an overview is given of the identified Space Missions with Sub One Kilogram Spacecraft, which is followed by a discussion of the obtained results. For the remaining three Chapters, Chapter 11 to Chapter 13, a selection of the mission characteristics is presented, as well as a graphical representation thereof. It is followed by an analyses as well as a discussion. Chapter 11 provides a closer look at the Launch Rates of the SSMs. In Chapter 12, the countries with SSMs are discussed, and in Chapter 13, the SSMs are categorized based on their SOKS.

Section III – The third section, Section III, contains the conclusions and recommendations for this thesis and contains one chapter, namely Chapter 14. It contains the conclusions based on the literature study in Section I and the Analyses and Discussion thereof in Section II. These conclusions are used to provide the outcome of the research questions and address the research statement. In the last part of this chapter, recommendations are provided based on the research and outcome of this thesis.

– SECTION I –

THE HISTORY OF SPACE MISSIONS WITH SUB ONE KILOGRAM SPACECRAFT

2

THE NEEDLES OF PROJECT WEST FORD

Intro – The first Space Mission with Sub One Kilogram Spacecraft (**SOKS**) was a result of the cold war in the late 1950s. Back then, the United States (**US**) stationed military forces all over the world. Intercontinental communication between these forces was provided by undersea cables and through reflection of radio waves by the ionosphere. The undersea cables provided reliable communication links but they were considered to be vulnerable to physical attacks. The ionosphere was considered to be less reliable for communication links due to its unpredictable nature, caused by natural phenomena like solar storms. In addition, the US had just discovered that the ionosphere was susceptible to thermonuclear detonations. This discovery increased the need for a new secure and reliable intercontinental communication system. Lincoln Laboratory, of the MIT (Massachusetts Institute of Technology), was assigned by the Department of Defense (**DOD**) to fulfill this need. Their proposed solution was referred to as Project Needles. Nowadays it is better known as Project West Ford. [2] [3]

Theory – The idea was to create an artificial belt around the Earth that would act as a new medium for the establishment of intercontinental communication links. This artificial belt, known as **Dipole Belt**, consists of millions of **Dipole Needles,** which are hair like wires, with a length equal to half the wavelength of the Electromagnetic Waves (**EMW**s) that are used for the transmission of the communication signals. This characteristic length causes the Dipole Needles to resonate with the transmitted EMWs and scatter them in all directions. A communication link is established by pointing a transmitting antenna and receiving antenna at the same point in the Dipole Belt (cf. Figure 2). The receiving antenna is not required to be in the field of view of the transmitting antenna. It is therefore possible to establish intercontinental communication links through the Dipole Belt. The Dipole Needles in the Dipole Belt are so small that they are not susceptible to physical attacks. Therefore, it is possible to provide also secure communication links. Reliable Communication Links can be provided by creating a permanent Dipole Belt with enough Dipole Needles. Thus, the Dipole Belt is suitable in providing the needs of a secure and reliable intercontinental communication system. However, it comes with many concerns that makes Project West Ford controversial. [2] [3] [4] [5] [6]

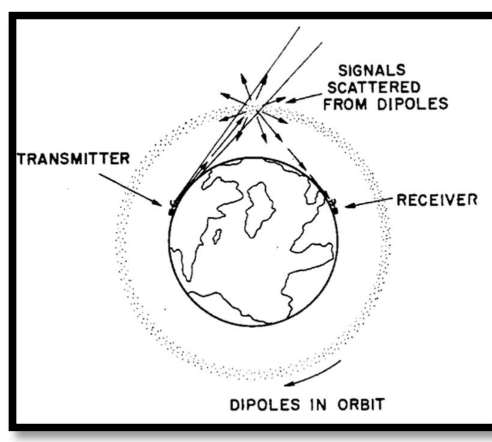

Figure 2: The Principles of Project West Ford. [4]

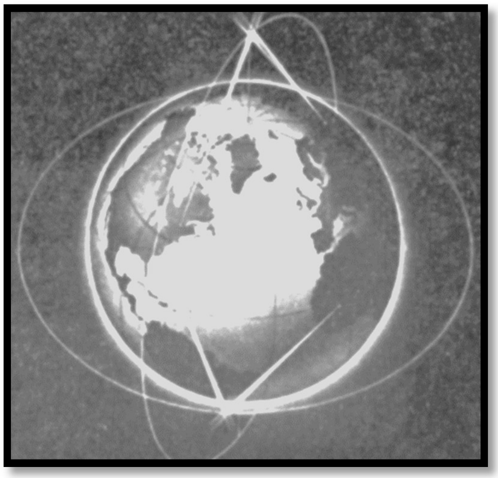

Figure 3: The Initial Concept of Project West Ford. [7]

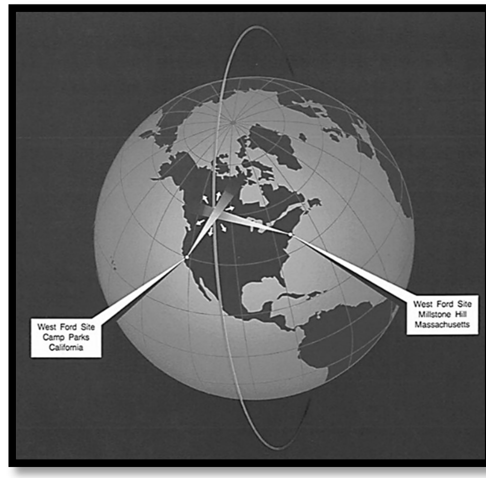

Figure 4: An artist impression of West Ford 1 and West Ford 2. [13]

Controversy –The effect of large concentrations of orbiting materials was unknown back then and raised a lot of concerns among several countries and scientists all over the world. The Dipole Needles in the Dipole Belt could interfere with other branches of science through scintillation, attenuation and scattering. Additionally, the scattering of sunlight could result in an increase of the insolation of the Earth and the sky temperature. Furthermore, placing this significant amount of Dipole Needles could result in a substantial increase of collision hazards in orbit. Another concern was that the Dipole Needles would end up as space debris. Even if they would not end up as space debris but re-enter the atmosphere, the fear was that the upper atmosphere could be polluted by the Dipole Needles and binder material. Another concern was overpopulation due to the successful demonstration of this concept. All these concerns could affect the course of future space missions and space research done on Earth, not only for the US but also for the rest of the World. The international relations could be at stake because of this or deteriorate even further. Placing a Dipole Belt into orbit was therefore quite controversial. Despite its controversy, two concepts were proposed. [2, 4, 7, 8, 9, 10, 11, 12]

West Ford Project – The initial mission concept proposed contains two permanent circular Dipole Belts around the Earth at an altitude of 8000 km. One Dipole Belt is placed in a polar orbit and another one is placed in an equatorial orbit. The polar Dipole Belt is used to establish a direct communication link between North America, Europe and Asia. The equatorial Dipole Belt is used to link North America directly with South America, Africa, Europe and Japan (cf. Figure 3). With these two Dipole Belts a global communication coverage can be provided that is reliable as well as secure. For convenience the initial mission concept is named **West Ford Project**. Whether the Dipole Belts in this concept could be created and actually be used for communication was yet to be proven. Next to that, the consequences of a Dipole Belt around the Earth were unknown. To prove that the concept works and to analyze the consequences of a Dipole Belt, another concept was proposed. [2, 4, 7, 14, 13]

West Ford Experiment – The second mission concept proposed contains only one exploratory Dipole Belt which is placed in a nearly circular polar orbit for a limited amount of time. To make sure that the Dipole Belt is temporary, a so called **Resonant Orbit** is used. A Resonant Orbit is an orbit around the Earth where the altitude of the perigee is decreased continuously over time by Solar Radiation Pressure (**SRP**) from the Sun. Eventually the orbit will cease to exist due to reentry in the atmosphere of the Earth. Once the dipole needles are deployed into orbit, the creation and the behavior of the Dipole Belt can be analyzed. A communication link is established between a ground station on the East Coast and the West Coast of the US to demonstrate that the concept works. To do this the ground track of the Dipole Belt needs to pass over North America (cf. Figure 4). For convenience this concept is named **West Ford Experiment**. [2, 4, 7, 13, 14]

Realization – The second mission concept, referred here as West Ford Experiment, was eventually realized. The first attempt was in 1961. Since it failed, another attempt was made in 1963. The creation of the Dipole Belt and the long distance communication concept was then successfully demonstrated. Furthermore, the consequences of the Dipole Belt were determined. No further attempts were made to create a Dipole Belt. This was mainly due to its controversy and the successful use of other communication spacecraft. For convenience the first attempt is named **West Ford 1** and the second attempt **West Ford 2**. [2 4 13]

2.1 WEST FORD 1

Intro – West Ford 1 was launched into orbit on the 21st of October in 1961 by the Atlas-LV3 Agena B launch vehicle as a piggyback on the MIDAS-4 spacecraft. It was supposed to be inserted into a Resonant Orbit at an altitude of about 3700 km which was nearly circular and polar. In total 350 Million Dipole Needles would then be expelled individually by a so called **Needle Dispenser**. The Needle Dispenser was nothing more than a cylindrical shell with closed ends (cf. Figure 5). Inside the cylinder the Dipole Needles were placed together with the binding material Naphthalene. Once in orbit, the MIDAS-4 spacecraft would eject the Needle Dispenser. During the ejection the Needle Dispenser starts spinning followed by the removal of the cylindrical shell. The naphthalene would then be exposed to the Sun and start to sublimate. The Dipole Needles are then dispensed individually in different directions and at different velocities due to the spinning and sublimation. The process of expelling individual Dipole Needles by a Needle Dispenser is commonly defined as **Dispensing**. After dispensing, the Dipole Belt will start growing due to the differences in the initial position and velocity of each Dipole Needle until it is finally completely formed. Once the Dipole Belt is formed, it will become gradually more diffuse (so called **Dispersion**) due to the placement of the Dipole Needles in the Resonant Orbit. In the worst case scenario, the last Dipole Needles were expected to return back into the atmosphere within 10 years. Unfortunately, the West Ford 1 mission turned out to go in a different way. [4 15 16]

Status – Shortly after the launch the booster of the launch vehicle had a roll-control failure. This caused the MIDAS-4 spacecraft together with West Ford 1 Needle Dispenser to be **injected** into the wrong orbit. After injection, the Needle Dispenser failed to spin during ejection from the MIDAS-4 Spacecraft. Subsequently the dispensing started, but instead of dispensing single Dipole Needles, clusters of Dipole Needles (so called **Dipole Clusters**) were dispensed. Due to the latter two events the Dipole Belt was never formed. The West Ford 1 mission was therefore a failure. The cause of the Dipole Clusters was determined from ground tests done after the launch. They seemed to be created during the impregnation between the Dipole Needles and the binding material Naphthalene which was done in vacuum. In certain conditions metals with a surface contact can weld in vacuum. During the impregnation some Dipole Needles had a surface contact with other Dipole Needles. Together with the vacuum condition this resulted in the forming of the Dipole Clusters. [10 15 17]

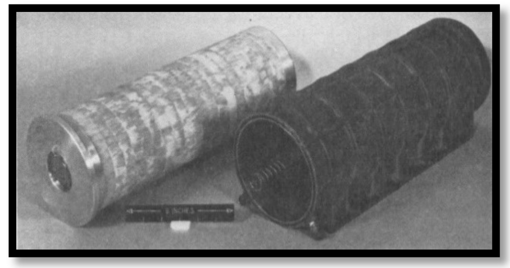

Figure 5: The West Ford 1 Needle Dispenser. [15]

Application – The main goal of West Ford 1 is to prove that a Dipole Belt can be created and that it can be used to provide long distance communication. Next to proving the concept, the creation and the behavior of the Dipole belt is analyzed for research purposes. Furthermore, the impact of such a belt on other branches of science like radio and optical astronomy is analyzed. Once the concept is proven, the Dipole Belt is used for communication purposes between the ground station in Millstone Hill and Camp Perks. The West Ford 1 mission is thus used for three applications, namely proof of concept, study of its orbital dynamics and communication. [2 3 18 19]

Spacecraft – West Ford 1 consists of 350 million spacecraft which are named for convenience **West Ford 1 Needles**. The payload of the West Ford 1 Needle is the spacecraft itself. The amount of subsystems that support the payload is therefore zero. It is made out of copper and has a cylindrical form with a height of 1,78 [cm] and a diameter of 25,4 [µm]. The density of the copper is assumed to be 8,94 [g/cm^3]. The volume and the mass of the West Ford 1 Needle are in this case calculated to be $9{,}02 \cdot 10^{-6}$ [cm^3] and 80,63 [µg] respectively. The payload to mass ratio is equal to one since the mass of the payload mass is equal to the total mass. [15 20 21]

2.2 WEST FORD 2

Intro – A second attempt to realize the West Ford Experiment was made on the 9th of May in 1963. West Ford 2 was launched by the same type of launch vehicle that was used for West Ford 1 (Atlas-LV3 Agena B), but now as a piggyback on the MIDAS-6 spacecraft. The aimed insertion orbit was again a resonant orbit at an altitude of about 3700 km that was nearly circular and polar. The Needle Dispenser that was used for West Ford 2 was an improved version of the West Ford 1 Needle Dispenser. A so called Telemetry Module (cf. Figure 6) was added so that the Needle Dispenser could be ejected from the MIDAS-6 spacecraft on command. This was to prevent that the Dipole Needles would end up in an orbit that was not desired as was the case for West Ford 1. The sequence of events after ejection remained unchanged. During ejection the Needle Dispenser starts spinning again and the outer shell is removed. Thereafter the Dipole Needles are dispensed at different velocities and in different directions due the sublimation of the binder material by the radiation of the Sun. The only difference now was that the 18 cylindrical decks was divided into 5 compartments instead of 1. This was to prevent that not all decks are affected in case there is again a spinning failure during ejection. Additionally, the impregnation technique of the Dipole Needles with the binding material Naphthalene was improved to prevent the forming of Dipole Clusters. The Dipole Needles used for West Ford 2 were changed as well. The length remained the same so that the same operation frequency could be used but the diameter of the Dipole Needles was decreased. This change was made to decrease the expected maximum orbital lifetime from 10 years to about 5 years. The amount of Dipole Needles was increased though from 350 Million to 480 Million. Despite these improvements, the West Ford 2 mission did not go exactly as planned. [4 9 15 22 23]

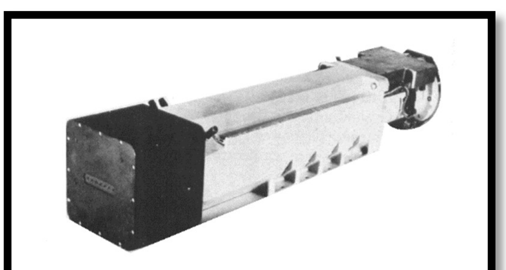

Figure 6: The West Ford 2 Needle Dispenser. The dark squared compartment is the Telemetry Module. [4]

Status – The launch vehicle injected the MIDAS-6 spacecraft together with West Ford 2 successfully into the right orbit. The next step was to send a command from the operation center to West Ford 2. The ejection of West Ford 2 from the MIDAS-6 spacecraft would then be initiated followed by the dispensing of the Dipole Needles. Unfortunately, this command was delayed by roughly 30 minutes. The delay was imposed by the operation center of the MIDAS-6 Spacecraft. This delay caused an uneven heating of the Needle Dispenser (cf. Figure 7) that resulted in a dispensing failure. It was estimated that not more than 50 percent of the Dipole Needles was dispensed individually. The other half of the Dipole Needles was dispensed as Dipole Clusters. Despite this failure, enough Dipole Needles were dispensed to create a Dipole Belt. The creation of the Dipole Belt could therefore be analyzed and long distance communication through this Belt could be tested. Furthermore, the effect of the Dipole Belt on other branches of sciences could be determined as well. West Ford 2 was therefore declared to be a successful mission. The cause of the forming of the Dipole Clusters was determined after the launch by subsequent tests on the ground. The end plates of the Needle Dispenser were connected by an inner cylindrical tube. Due to the delay, one end plate got

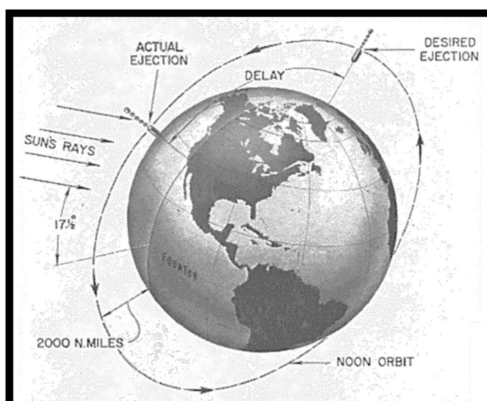

Figure 7: Visualization of the desired and actual ejection of West Ford 2. [15]

heated (cf. Figure 7). This caused the inner cylindrical tube to be heated as well. The binder material started therefore to sublime already from the inside before the dispensing was started. This caused some Dipole Needles to have a needle on needle contact. Together with the vacuum condition it resulted in the welding of Dipole Needles and the creation of Dipole Clusters. [4 9 15 19]

Application – The main goal for West Ford 2 remained the same as for West Ford 1. The main goal for West Ford 1 was to prove that a Dipole Belt can be created and that it can be used for long distance communication. Furthermore, the creation and the behavior of the Dipole Belt is analyzed for research purposes as well as the effect of such a belt on other branches of science. The applications proof of concept, study of its orbital dynamics and communication are therefore also applicable for West Ford 2. [18 19 6]

Spacecraft – The amount of spacecraft for West Ford 2 is increased from 350 million to 480 million with respect to West Ford 1. This is an increase of about 37 percent. For convenience these spacecraft are named West Ford 2 Needles. The payload of the West Ford 2 Needle is again the spacecraft itself. This means that there are no subsystems that support the payload and that the payload to mass ratio is equal to one. The design of the West Ford 2 Needle is the same as the West Ford 1 Needle with the exception of the diameter. The diameter is decreased about 30 percent from 25,4 [μm] to 17,8 [μm]. The form (cylindrical), material (copper) and the length (1,78 [cm]) remain unchanged. The volume and the mass can be calculated by using the density of copper (8,94 [g/cm^3]). They are about half the values calculated for West Ford 1, namely $4{,}43 \cdot 10^{-6}$ [cm^3] and 39,6 [μg] respectively. The calculated mass is in accordance with the given mass, which is about 40 [μg]. Based on the mass the West Ford 2 Needle, the spacecraft can be classified as yocto spacecraft, as was the case for West Ford 1. [13 15 20]

2.3 WEST FORD DRAG

Intro – Another Space Mission with Dipole Needles, nowadays better known as West Ford Drag (**WFD**), was launched in 1962. It seems that the launch took place on the 9th of April of that year. Lincoln Laboratory was this time assigned by the DOD to analyze the effect of Charge Drag on Dipole Needles in a circular polar orbit with an altitude of 3100 [km]. [24 25]

Status – The Dipole Needles of WFD were successfully placed in orbit. In the end, it was concluded that the effect of Charge Drag at that altitude was negligible. The WFD was therefore considered to be a successful mission. [25]

Application – The main goal of this mission was to determine whether Charge Drag had a significant effect on the orbit of the Dipole Needles. **Charge Drag** was then defined as the drag that was a result of the exerted Coulomb's Force on the Spacecraft due to electric charge differences. It was believed that it could decrease the mean altitude of the Dipole Needles. The idea was to measure this decrease by studying their orbital elements. Therefore, an orbit was required in which other orbital perturbations could be assumed to be negligible, hence the altitude and form of the orbit. The main application for West Ford Drag is thus basically research on the orbital perturbations through the study of the Orbital Dynamics. [26 24 25 27]

Spacecraft – In total, six Dipole Needles were used for WFD. They were each 34 [cm] long and had a diameter of 0,043 [cm]. Although the mass was not given, it was estimated by assuming it was also made out of copper, just like the Dipole Needles of West Ford 1 and West Ford 2. In that case, the mass was calculated to be about 0,44 [g] for each WFD Needle. [24 25]

3

THE TETRAHEDRAL ENVIRON MENTAL RESEARCH SATELLITE

Intro – At the beginning of the Space Age in 1958 the US and the Soviet Union (**USSR**) started to analyze the effects of nuclear explosions at high altitudes. The so called **High Altitude Nuclear Explosions** (**HANE**) took place at altitudes ranging from roughly 20 to 600 [km]. One of the HANE findings in 1958 was that the ionosphere was susceptible to thermonuclear detonations. This finding contributed to the need for a new secure and reliable intercontinental communication system by the US which lead eventually to Project West Ford. Another finding of the HANE was the creation of artificial radiation belts due to the energetic particles that got trapped by the magnetic field of the Earth. Little was known about these artificial radiation belts until the HANE on the 9th of July in 1962 at an altitude of about 400 [km]. This was the largest HANE that ever took place in history and is nowadays known as Starfish Prime. The created artificial radiation belt seemed to be causing significant more radiation damage on spacecraft than the recently discovered natural radiation belts known as the Van Allen Belts. One of the spacecraft that observed the created Artificial Radiation Belt (Ariel I) went into intermittent operation three days after the artificial belt was created. One month later, two more spacecraft that observed this radiation belt (Traac and Transit 4B) stopped being operational. In the subsequent month's other spacecraft that were passing this region ceased to operate as well. The artificial radiation belt could thus be used to disable spacecraft in orbit. The United States Air Force (**USAF**) had therefore the need to do more research on artificial radiation belts as well as the shielding possibilities of spacecraft against these radiations. The unexpected loss of the costly spacecraft led also to the need to do this research with less costly spacecraft. These events together with the created needs contributed to the start of the Environmental Research Satellite (**ERS**) program and the use of the second type of Sub One Kilogram Spacecraft which is nowadays known as the Tetrahedral Research Satellite (**TRS**). [28] [29] [30] [31] [32]

Theory – The subsidiary Space Technology Laboratories of the American corporation **TRW** (Thompson Ramo Wooldridge, nowadays part of Northrop Grumman) offered, independently of the ERS program, the Tetrahedral Research Satellite on the space market. The TRS was a tetrahedron shaped spacecraft and could be used for research in space near the Earth. It could also be used to test components of future generations of spacecraft in space. The characteristics of the TRS were the relative low spacecraft and launch cost, simple spacecraft integration and a short fabrication and lead time. The launch cost could be reduced by designing the TRS specifically for piggyback launches. The spacecraft cost could be reduced by offering a relatively small simple integrated spacecraft that could do a limited amount of experiments instead of a relative big and complex integrated spacecraft that could do many experiments. Furthermore, the spacecraft was not designed around the payload but the payload needed to be designed to fit the spacecraft with the provided subsystems. The idea was to provide a spacecraft with standardized subsystems that could support different kind of payloads. The provided spacecraft could be produced multiple times without changing the fabrication process and could be installed with different kind of experiments. The last characteristic of the TRS was that with one Launch Vehicle multiple TRS could be launched in either the same or multiple orbits. The TRS could thus be used for so called **Multiple Payload Launches** (**MP**L) combined with **Multiple Orbit Launches** (**MOL**). These type of spacecraft seemed to be fulfilling the needs USAF had due to the created artificial radiation belts. They were relatively inexpensive, could be used for scientific research in space and act as a test bed in space for new spacecraft components. TRW was therefore assigned by the USAF to provide the spacecraft for their ERS program. [33] [34] [35] [36] [37]

ERS – The Space Systems Division of USAF was the first to order spacecraft for the ERS program. They ordered six TRS from TRW that would act as the first six ERS. After the successful use of some of these TRS, more ERS were ordered from TRW. The first ten ERS were all part of the same TRS family, also known as TRS Mark I. The ERS that followed thereafter were part of the TRS Mark II family. These TRS were similar to the TRS of the TRS Mark I family, but then bigger in size and mass. The next generation of ERS were part of the Octahedral Research Satellite (**ORS**) Mark II family. As the name suggests, the spacecraft had an octahedron form. The size and the mass had again increased compared to the previous two generations. The following generation of ERS were part of the ORS Mark III family, which was basically the same as the ORS from the ORS Mark II family but then again bigger in size and mass. The last two families of spacecraft used for the ERS program were named OV5 (Orbiting Vehicle 5) and the Test and Training Satellite. The spacecraft were not only ordered by the space department of the USAF but also by other departments like the Office of Aerospace Research. In the end USAF was the only one that ordered the spacecraft that were offered on the space market by TRW (cf. Figure 8). Throughout the years the mass of the ERS increased from about 0,7 [kg] to about 45 [kg]. The ERS from the TRS Mark I family were the only ERS that can be classified as SOKS since they are assumed to all have a mass lower than 1 [kg]. The TRS Mark I family is therefore the only family of spacecraft from the ERS program considered here. [34] [37] [38] [39] [40]

Spacecraft – The TRS that belong to the TRS Mark I family have the same form and size. Spacecraft thathave these characteristics or are assumed to have these characteristics are referred here as **Congruent Spacecraft**. Even though these TRS look the same, they are not by definition identical. In case the spacecraft are identical or are assumed to be identical they are referred here as **Twin Spacecraft**. The payload of congruent TRS can differ from TRS to TRS. On the other hand, the set of subsystems that support the payload of each of these TRS is assumed to be more or less the same. Some of these subsystems are slightly customizable and or modifiable though. The mass of the subsystems can therefore differ somewhat from TRS to TRS. These differences are assumed to be negligible for now unless stated otherwise. Spacecraft Subsystems that are designed to be used for a range of spacecraft that can support a range of payloads are for convenience referred here as **Standardized Subsystems**. The TRS from the TRS Mark I family can therefore be seen as **Congruent Spacecraft** with a payload that can differ from spacecraft to spacecraft and is supported by a set of slightly customizable and or modifiable **Standardized Subsystems** that are assumed to be more or less the same for each spacecraft. These kind of spacecraft are also referred as **General Utility Spacecraft** (**GUS**) at the end of the 1960s. For convenience the GUS that belongs to the TRS Mark I family is named **TRS I**. The TRS I (cf. Figure 9) represents thus the general layout of the TRS from the TRS Mark I family. This outline is assumed to be the same for the launched TRS from the TRS Mark I family as well unless stated otherwise. The TRS I can have a variable payload that is supported by standardized subsystems. The given minimum mass of the TRS I is about 680 [g]. [33]

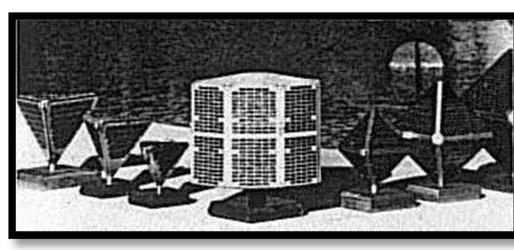

Figure 8: The General Utility Spacecraft offered by TRW. The second, third, sixth and seventh spacecraft from left are known as respectively TRS Mark II, TRS Mark I, ORS Mark II and ORS Mark III. [41]

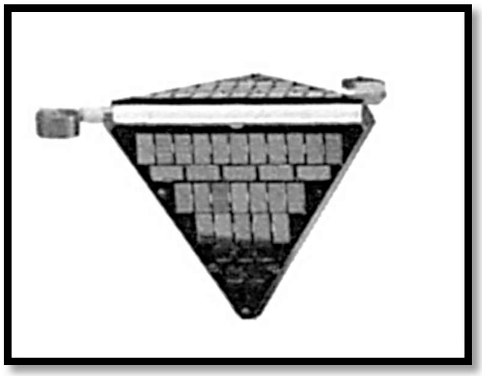

Figure 9: The Tetrahedral Research Satellite of the Mark I Family. Two stowed Antennas are attached to its exterior. Each solar Panel contains 28 Solar Cells that are used for the Power System. The five, so called, Test Cells are reserved for the payload. [35]

Realization – The first 10 spacecraft used for the ERS program are TRS from the TRS Mark I Family. They are launched between 1962 and 1963 and are often referred to as ERS-1 to ERS-10. The number added to ERS indicates in principle the launching order with the exception of ERS-1 and ERS-2. The launch of ERS-1, which was planned before the launch of ERS-2, was delayed and was therefore launched after the launch of ERS-2. In addition, TRS is often added to the name of these ERS spacecraft in case the mission was a success or a partial success. The number added to TRS indicates in principle the order in which the spacecraft were successful. An exception to this rule is ERS-1, which is sometimes referred to as ERS-1/TRS. The mission of this spacecraft was not a success but the TRS is still added to the name of the spacecraft but without a number though. The TRS in the spacecraft name does not indicate the family of the TRS. The ERS launched after ERS-10, can contain also TRS in their name in case the mission was a success and the spacecraft looked like a tetrahedron, even though they are from the TRS Mark II family like ERS-12/TRS-5. ERS-1 to ERS-10 are the only ERS that are considered to be Sub One Kilogram Spacecraft since it is believed that they had a mass smaller than one kilogram. All these ERS are assumed to have the same mass as TRS I Min unless stated otherwise.

3.1 ERS-1/TRS

Status – The ERS-1, often referred to as TRS, was launched into orbit on the 11th of November in 1962, presumably, by the Atlas-LV3 Agena B launch vehicle as a piggyback on SAMOS-11 (Satellite And Missile Observation System). It did not separate from the aft rack of the Agena B booster that returned back to Earth on the 12th of November in 1962. The mission was declared as a failure since no data was obtained from the ERS-1. [35 38 42 43 44]

Application – Information about the payload was undisclosed, but it is believed that the ERS-1 was either equipped with radiation instruments that would later be used for the Vela Spacecraft or that solar cells were used to measure the radiation damage. The radiation instruments should detect radiation, in this way nuclear explosions in space could be observed. The application of ERS-1 in that case can be categorized as Technology Demonstration since the instrumentations are installed to see if they work. In case the solar cells are used for radiation damage, the application can be categorized as Research and Scientific Research. The radiation damage on solar cells can be used to analyze the shielding properties of spacecraft as well as determining the intensity of the radiation in space. [36 44 45 46]

3.2 ERS-2/TRS-1

ERS-2/TRS 1

Status – The ERS-2, which is often referred as **TRS 1**, was the first TRS from the TRS Mark I family to be launched. It was launched into orbit on the 17th of September in 1962 by the *Thor Agena B* launch vehicle as a piggyback on the *Discoverer 51*. On the 13th of November in 1962 it was announced that the ERS-2 mission was successful. Despite that the ERS-2 failed to deploy from the aft rack of the Agena B booster that stayed attached to the Discoverer 51, it managed to send back useful data. On the 19th of November, 1962, the ERS-2 re-entered the atmosphere of the Earth. [34 38 42 43 45]

Application – The ERS-2 is used to study the radiation intensity of the artificial radiation belt created by Starfish Prime as well as its radiation damage effect on different type of solar cells. The four sets of five solar cells per solar panel are used for this study. The so called test solar cells differ from the conventional solar cells used for the rest of the solar cells. The different types of calibrated test solar cells used is not given but it is given that they are used to study which solar cells are suitable for future generations of spacecraft and provide a range of radiation measurements. The solar cells did not have any shielding. The intensity of the artificial radiation belt is assumed to be derived from the measured solar cell degradation. Thus the ERS-2 is used for Scientific Research (Study of the Artificial Radiation Belt) as well as Technology Demonstration (Testing New Types of Solar Cells). The total mass of the ERS-2 is given to be about 0.67 [kg] (1.47 [lb]), which is roughly 10 [g] less from the TRS I. The Power supply is approximately about 600 [mW], which is about 0.2 [W] less than the regulated power that is given for the TRS I. For convenience these differences are assumed to be negligible and are therefore not considered. The ground stations could receive up to 8 minutes of solar cell data on each favorable pass. [34 44 47 48]

3.3 ERS-3, ERS-4

Status – The ERS-3 and the ERS-4 are launched together on the 17th of December in 1962 by the Atlas Agena B Launch Vehicle as a piggyback onboard of one of the MIDAS spacecraft. During the ascent phase a malfunction occurred in the launch vehicle. It is believed that 80 seconds after the launch the launch vehicle got off track and that it got destroyed by its range safety system. Thus, the ERS-3 and ERS-4 mission failed due to a launch vehicle malfunction. [35 36 44]

Application – The payload for the ERS-3 and the ERS-4 is undisclosed. It is believed though that they carried a Cosmic Ray Experiment and Infrared Plume Experiment. Further details about these experiments are not given. Based on the name of these experiments it is assumed that the Cosmic Ray Experiment is used to measure (high) radiation levels in orbit. The Infrared Plume Experiment is assumed to be an instrument that is planned to be used for future generations of spacecraft that should detect objects with a plume like launch vehicles or missiles. It is furthermore believed that the damage of the solar cells is measured for the study of radiation and micrometeorites in orbit. The ERS-3 and ERS-4 seem to have been used for Scientific Research as well as Technology Demonstration. Whether they are both equipped with the same experiments or whether the experiments are divided by both spacecraft is not known, although it is implied that the ERS-3 and ERS-4 are seen as Twin Spacecraft. The mass of these ERS is not given. Theoretically speaking they can be compared to both TRS I defined in the mass budget section of TRS I but based on the amount and the type of experiments and the insinuation that the ERS-3 and ERS-4 are Twin Spacecraft, it is assumed that they are comparable to TRS I Max. The preferred orbit for the ERS-3 and ERS-4 is not known. The same goes for the Expected Mission and Orbital lifetime. Based on the definition of the Project Realization Time, the it can be set to roughly 2 months. [36 44 49]

3.4 ERS-5/TRS-2, ERS-6/TRS-3

Status – The ERS-5 and ERS-6, often referred to as TRS 2 and TRS 3, are launched together by the Atlas Agena B Launch Vehicle on the 9th of May in 1963 as piggybacks onboard, what is believed to be, the MIDAS 6 Spacecraft. These ERS are successfully launched into orbit and managed to send back valuable data. The mission of ERS-5 and ERS-6 is therefore seen as a successful Mission. [38 39 50 51 52]

Application – The ERS-5 and ERS-6 are used to study the radiation intensity of the Van Allen Belts. They are also used to study the degradation of unshielded solar cell degradation due to this radiation. Furthermore, some of the test cells are covered with fused quartz and glass of microscopic thickness for the study of shielding properties of solar cells against this radiation. These experiments are sometimes also referred to as Solar Cell Damage Experiments. The ERS-5 and ERS-6 are thus used for Scientific Research (i.e. Radiation Intensity Van Allen Belts) and Technology Demonstration (i.e. Solar Cell Shielding). It is believed that ERS-5 and ERS-6 are equipped with the same experiments so for convenience they are assumed to be Twin Spacecraft. The mass of each of these ERS is given to be about 0,68 [kg] (1,5 [[lb]). It is given that these ERS are equipped with 132 Solar Cells each which means that all the test cells are indeed used. [35 36 39 50 52 53 54]

3.5 ERS-7/ERS-8

Status – The ERS-7 and ERS-8 are launched together on the 12th of June in 1963 by the Atlas Agena B Launch Vehicle as a piggyback onboard the *MIDAS 8* spacecraft. Shortly after the launch the launch vehicle exploded and the spacecraft burned up in the atmosphere. The ERS-7 and ERS-8 mission failed thus due to a malfunction in the launch vehicle. [36 50 51]

Application – It is believed that ERS-7 and ERS-8 are used to carry out radiation and micrometeorite experiments. It is not clear if they both would carry out the same experiments or whether one ERS would do the radiation experiment and the other would do the micrometeorite experiment. The radiation experiment could be interpreted as either testing of new equipment that measures radiation in orbit or as using the solar cell degradation to measure the radiation in orbit. For the micrometeorite experiment it seems likely that available solar cells for experiments are used. Whether they would be used to count the micrometeorites impacts or whether new solar cells are tested against micrometeorites is not clear either. Thus several applications are possible, for now it is assumed that they are both used for Technology Demonstration and Scientific Research. The mass is believed to be about 0,7 [kg]. Further details about the desired orbit are not given. [36 51 55]

3.6 ERS-9/TRS-4, ERS-10

Status – The ERS-9 and ERS-10 are launched together on the 19th of July in 1963 by the Atlas-*LV3* Agena B Launch Vehicle as a piggyback on, what is believed to be, the MIDAS 7 Spacecraft. The ERS-10 failed to deploy and did not send any data which resulted in a failed mission. The ERS-9 is successfully deployed and managed to send back useful data. The ERS-9 mission is thus successful. It is the fourth TRS from the TRS Mark I family that is successful and is therefore often referred to as TRS 4. The information collected from ERS-9 correlated with the data obtained through ERS-5 and ERS-6. [38 42 43 50 56]

Application – The ERS-9 and ERS-10 are believed to be Twin Spacecraft. They are used to study the radiation damage on their solar cells probably due to the Van Allen Belts. It is believed that from the 132 solar cells 20 solar cells are used for this. Some of them are covered with a shield that has a thickness of either 0.15 [mm], 0.5 [mm] or 1,5 [mm] or are left unshielded. The ERS-5 and ERS-6 are believed to have some test cells that are covered with a shield that has a thickness of either 0.5 [mm] or 1 [mm] or are left unshielded. The proposed payload seems to be in accordance with the given information that the data of ERS-9 correlated with the data obtained from ERS-5 and ERS-6. It is further more believed that the solar cell degradation is used to determine the intensity of the radiation in orbit. The ERS-9 and ERS-10 are thus used for Scientific Research (i.e. Radiation Intensity, probably from the Van Allen Belt) and Technology Demonstration (i.e. Solar Cell Shielding). The first values made public indicated that the mass of ERS-9 and ERS-10 are each about 0.68 [kg] (1,5 [lb]). It seems likely that the standard value of 1.5 [lb] is used for each TRS from the TRS Mark I Family since at that time this information is in general not made public because it was a DOD spacecraft. Some years thereafter the mass that is made public is changed to 0.8 [kg]. For now, the mass of 0.8 [kg] is used for their mass budget ERS-9 and ERS-10. The only difference is that the payload mass is increased by roughly 0.1 [kg]. [35 36 38 42 50]

4

THE CALIBRATION SPHERES

Intro – With the successful launch of Sputnik I in 1957, the USSR did not only initiate the start of the space age, they also triggered the fear of hostile objects in space which was seen as a serious threat by the US considering the Cold War. The US had therefore the need to detect, track and catalog artificial objects in space and monitor space activities, which is nowadays often referred to as **Space Surveillance**. The International Geophysical Year (**IGY**) Minitrack Network that just was installed back then could only track Earth orbiting spacecraft that had a so called tracking beacon onboard. The **Tracking Beacon** is actually nothing more than a transmitter that operates at the same frequency as the receivers of the IGY Minitrack Network. Spacecraft transmitting at other frequencies could therefore not be tracked unless the receivers of the IGY Minitrack Network were adjusted to the same transmitting frequency of the spacecraft. This limitation became apparent when the US wanted to track Sputnik I, which transmitted a signal at a different frequency. Another limitation was that spacecraft without a transmitting beacon could not be detected and tracked, like the West Ford 1 Needles. The IGY Minitrack Network was therefore not suitable to fulfill all the needs concerning Space Surveillance. A different solution was needed so shortly after the launch of Sputnik I the US assigned different branches of the United States Armed forces to fulfill the Space Surveillance needs. Eventually this effort resulted in the Space Detection and Tracking System (**SPADATS**) that was placed under the North American Air Defense Command, also known as **NORAD** (nowadays North American Aerospace Defense Command). SPADATS was a Space Surveillance Network consisting of several Space Surveillance Systems that were developed and build by different agencies within the US. One of the Space Surveillance Systems was known as **SPACETRACK**, which was a result of **Project Space Track** and was developed by USAF. This Space Surveillance System made eventually use of Ground Based as well as Space Based Space Surveillance Systems. The TRS that measured radiation can be seen for example as one of the Space Based Space Surveillance Systems because they are used for monitoring activities in space. The US Navy contributed as well to SPADATS by developing a Space Surveillance System that was initially known as SPASUR (Space Surveillance) and is often referred to as **Space Fence**. To indicate that this Space Surveillance System was developed by the Navy it was later referred to as **NAVSPASUR** (Naval Space Surveillance). Nowadays NAVSPASUR is known as the Air Force Space Surveillance System due to the transfer of the system to USAF in 2004. After SPADATS became fully operational in 1961, it was soon realized that the Space Population kept increasing steadily and that this Space Surveillance Network needed to be improved to satisfy the military needs. The measures that were taken to do this involved improving existing Space Surveillance Systems as well as developing other advanced Space Surveillance Systems. The need for improvement of Space Surveillance Systems resulted eventually in the third type of Sub One Kilogram Spacecraft known as **Calsphere**, which stands for Calibration Sphere. [21 57 58 59]

Theory – One of the ways to do Space Surveillance at that time was by means of Radar. **Radar** is defined here as a system that uses Electromagnetic waves for detection and ranging purposes. The detection and ranging is done by transmitting Electromagnetic waves and analyzing the received transmitted Electromagnetic waves after they interacted with objects that were in their direction of movement (cf. Figure 10). The term Radar initially stems of from RADAR, which stands for Radio Detection and Ranging. As the abbreviation already suggests, **RADAR** is a system that uses Radio Waves for detection and ranging purposes. It is therefore often assumed that Radar uses by definition Radio Waves, which is nowadays not the case anymore. The different kind of Radars are mainly classified by either the type or frequency of the EMW used (e.g. Microwave Radar, Very High Frequency Radar), the configuration (e.g. Bistatic Radar, Doppler Radar), the application (e.g. Weather Radar, Space Surveillance Radar), or the placement (Ground Based Radar, Space Based Radar). In some cases, new names are introduced based on these classifications like with LIDAR, which stands for Light Detection and Ranging. The detection and ranging method however remains basically the same for all kinds of Radars. The objects that are detected by radar can be expressed by their so called Scattering Cross Section. Nowadays it is often referred to as the Radar Cross Section (**RCS**). The **Radar Cross Section** is basically the ability of an object to **scatter** the transmitted EMWs in the direction of the receiver of the radar. This parameter usually varies in time for each object since it depends on parameters that vary in time as well. Despite the variations in RCS, the objects can still be distinguished from each other and can therefore be tracked. Orbiting Spacecraft of which the position in time is known are used to verify if the radar can detect them. They are often not suitable though to check if the measured RCS is the same as the expected theoretical RCS since the measured RCS varies in time and the theoretical RCS of these spacecraft difficult to obtain. In other words, the RCS observed by the radars cannot be calibrated with these spacecraft. For the detection and tracking this is not an issue but for deriving the properties of the object based on the RCS it is. As part of the improvements of the Space Surveillance Systems at the beginning of the 1960 a need was created to calibrate the radars. The radars can be calibrated by placing an object in space of which the measured RCS is more or less the same and of which the theoretical RCS can be determined. One of the parameters that influences the RCS is the so called Projected Cross Sectional Area (**PCSA**). The **Projected Cross Sectional Area** is basically the shape of the object that is seen with respect to the radar. An object that has a constant PCSA for example is a sphere. No matter from what direction the sphere is observed, it will always appear as a circle. Another parameter that influences the measured RCS is the direction in which the EMWs are scattered every time it interacts with the EMWs that are transmitted by the radar. For a uniform scattering pattern, independent from where the EMWs are transmitted, a sphere with a smooth surface is required that is made out of one material. The material is of importance for the RCS since it determines the strength of transmitted EMWs that are scattered. The ideal material is therefore preferred to have no or low absorptivity and transparency, which means in other words a high reflectivity. With a perfectly smooth reflective sphere the theoretical RCS is only dependent on the size of the object that can in this case be expressed by the radius (or diameter) of the sphere and the wavelength (or frequency) of the transmitted EMW. The relation between the theoretical RCS (divided by the PCSA of the sphere) with respect to the Circumference of the sphere (divided by the transmitted wavelength) is known (cf. Figure 11). From this relation it is known that from a certain wavelength (or frequency) and size of the sphere, the RCS (divided by the PCSA) is equal to one, and therefore independent of the frequency (cf. Figure 11). This scattering behavior is often referred to as the **Optical Scattering Region**. The scattering in this region is the ideal case for calibrating the radar since the RCS is then equal to the Cross Sectional Area of the sphere. The other scattering regions (**Rayleigh** and **Mie**) are not preferable for calibration since the RCS depends strongly on the

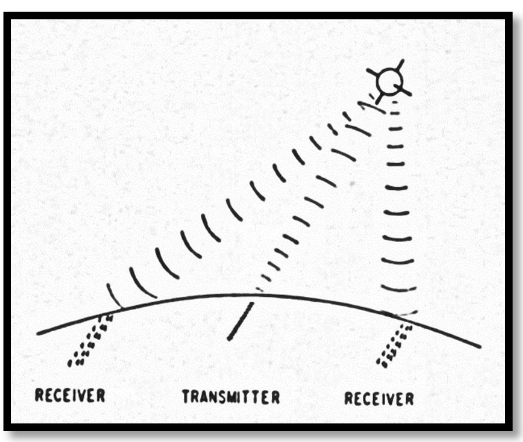

Figure 10: The principles of detecting objects in space by radar. This radar system is, based on its configuration, often referred to as Bistatic Radar. [60]

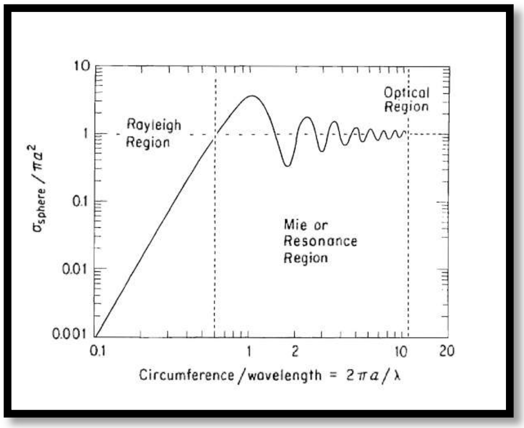

Figure 11: The Radar Cross Section of a Smooth Reflective Sphere at different Wavelengths. [61]

wavelength (or frequency) used. Based on the frequency of the transmitted EMW the size of the calibration sphere can be determined. Next to the ideal object for calibration, there is also an ideal orbit for the placement of the calibration object. In order to check other properties of the radar like the Antenna Gain, Effective Power and Signal-Level Measurement, the object should be placed in an orbit with an altitude that is low enough to yield a high signal to noise ratio. On the other hand, to check the system probability of detection, the signal to noise ratio should be marginal, which indicates an orbit with a high altitude. A relative eccentric (in other words, elliptical) orbit is therefore preferred to fulfill these needs. In order for other radars to be served as well a high inclination orbit is preferred. [57 61 62 63 64]

Realization – The idea back then of using smooth reflective spheres for the calibration of radars that were used for the Space Surveillance Network of the US lead eventually to the family of spacecraft that is nowadays known as the Calsphere family. Four Spacecraft of this family are considered to be Sub One Kilogram Spacecraft. One of them was part of the so called **Dual Calsphere Experiment** that was launched in 1964. The remaining three Calspheres were launched in 1971 as part of the so called Triple **Calsphere Experiment**. [57 65].

4.1 DUAL CALSPHERE EXPERIMENT

Intro – The Naval Research Laboratory (**NRL**) got an opportunity to launch a piggyback spacecraft for calibration purpose. This opportunity was presented by the Bureau of Naval Weapons on behalf of the US Navy. The idea was to launch the aforementioned desired calibration sphere to calibrate the radars of NAVSPASUR, which were used back then for Space Surveillance. Launching this calibration sphere with the desired size was not possible due to the limited space that was available for piggybacking. The preferred orbit was also not exactly as desired since the orbit was limited by the orbit of the main payload of the launch vehicle. On the other hand, the available mass for piggybacking was less restrictive. Next to that, the orbit of the primary payload was a region that was poorly covered. An alternative mission is therefore proposed. The proposed mission consists of two Calibration Spheres instead of one. The Calibration Spheres are both smaller in size then the desired Calibration Sphere. They are furthermore identical with the exception of the mass. In other words, they are congruent spacecraft. The idea was to place these objects into the same orbit and use them as so called standard targets for calibration of radars in the future. In the meanwhile, the orbital parameters of both calibration spheres are observed to serve other studies. These studies are mainly possible due to the difference in spacecraft mass. The lighter sphere is known as **Calsphere 1** (**CS1**) and has a mass of less than one kilogram. The heavier sphere, named **Calsphere 2** (**CS2**), is about 10 [kg] and is therefore not considered to be a Sub One Kilogram Spacecraft. Together they form the so called **Dual Calsphere Experiment**. They are both launched on the 6th of October in 1964 by the Thor-Ablestar Launch Vehicle as piggyback spacecraft onboard the Transit 5B-4 Spacecraft. [42 57 66 67 68]

Status – Each Calsphere of the Dual Calsphere Experiment is placed in a so called Launching Cradle. The Launching Cradles are attached to the payload adapter of the launch vehicle. Once the launch vehicle has reached the right insertion orbit the separation of the main payload is initiated. Eight minutes after this separation both Calspheres are expected to be deployed in the same orbit with the same deployment velocity. Once they are deployed the spacecraft can be used for calibration purposes and their orbital behavior is monitored. In the end the launch vehicle reached the right insertion orbit and the main payload separated as planned. The deployment of the Calspheres on the other hand did not go as expected. Based on the obtained observations it seems like the deployment started 18 hours after the launch. From ground tests it seems that the subliming switch that would start the deployment did not function. Due to the space environment the material slowly sublimed and the deployment was still initiated. Despite the failure in the deployment system the launch is still considered to be a success. The orbital elements are thereafter observed and have proven to be useful for different kind of studies, even for studies nowadays. At the moment of launch, the Calspheres were ideal targets for determining the degradation in the probability of detection. This was because they are detected relatively rarely. Whether these Calspheres are eventually used for the calibration of radars is not known but they could be used for certain radars and therefore the mission is assumed to be seen as a success. [57]

Application – Calsphere 1 acts as a so called standard target for future use. A **Standard Target** is seen here as an object that is placed in an orbit in space for calibration purposes. In this case it is placed in orbit to calibrate in particular future radars of which the transmitted EMWs scattered by CS1 behave as in the so called Optical Region. This region starts more or less when the circumference of the calibration sphere (divided by the wavelength of the transmitted EMWs) is about 10 (cf. Figure 11). Based on the given diameter of CS1 (35,56 [cm] (14 [in])) the circumference is calculated to be 111,72 [cm]. CS1 is thus intended for the calibration of future radars that transmit EMWs with roughly a frequency of at least 3 [GHz] (2,68 [GHz]) or with a wavelength not more than about 10 [cm] (11.17 [cm]). Depending on the classification, it means that Microwave Radars, Super High Frequency Radars or S-Band Radars are the limit. The radars of NAVSPASUR, for which the mission was initially intended, are Radio Wave Radars and could therefore not use CS1 for calibration. They operated at that time at a frequency of 108 [MHz] ([Mc]). At this frequency the transmitted EMWs that are scattered by CS1 behave as in the Rayleigh Region according to the value of the circumference of the calibration sphere divided by the wavelengths (which is calculated to be 0,4). Despite this, CS1 was still of use for the radars of NAVSPASUR, in particular for the determination of the Detection probability since the altitude of the orbit of CS1 was high enough. With the planned transition of the operation frequency to 216 [MHz] ([Mc]) as well as the increase of the Transmitter Power the improvement of the Detection Probability of these radars is well measured. The increase in operation frequency was nevertheless not enough to use CS1 for the intended calibration. The scattering behavior did change to the Mie Region based on the calculated circumference of the calibration sphere divided by the wavelength of the transmitted EMWs, which is equal to 0.8. Calsphere 1 together with CS2, serve a different purpose. Their orbital behavior over time is observed by NAVSPASUR and compared with each other for atmospheric research. It was assumed that the atmospheric drag was the main perturbation for these Calspheres. They are therefore also referred to as **Dragspheres**. The Orbital Perturbations due to SRP are neglected due to the relative low Area to Mass Ratio of both spacecraft and the negligible orbital eccentricity. Other perturbations are neglected as well. With these simplifications the change in semi major axis over time can be related to only the density at the orbital altitude. All the other parameters in this relation like the Mass and PCSA are known. The only value that is assumed is the Drag Coefficient of the spheres. For spheres a value of 2 is often used back then. Both Calspheres orbit in the same orbit so similar densities are expected. The difference in the obtained densities while they are in the same orbit are used to estimate a more realistic value for the drag coefficient of the spheres. The derived densities from the Dual Calspheres are also used to validate the theoretical density models at these altitudes. The density variations over time are furthermore used to analyze the correlation to the Solar Activity. The decrement in semi-major axis is also used to determine the lighter Calsphere from the heavier Calsphere. The Dual Calsphere Experiment is thus used for two applications, namely calibration and atmospheric research. [57] [68] [69] [70] [71] [72]

Spacecraft – The payload of the CS1 Spacecraft is the spacecraft itself. There are no subsystems onboard to support the payload. The shape of the CS1 Spacecraft is, as its name suggest, a sphere. The sphere is hollow and consists therefore of two hemispheres that are welded together. The surface of the sphere is furthermore polished to create a smooth surface. The diameter of the sphere is given to be roughly 35,56 [cm] (14 [in]). There is also a so called mounting hole in the sphere that has a diameter of roughly 0,953 [cm] (3/8 [in]). The material used for the sphere is an aluminum alloy that has a thickness of about 0,794 [cm] (1/32 [in]). The aluminum alloy used is given to be Aluminum 5052-H32. The density of this alloy seems to be about 2,68 [g/cm^3], which is about 56,99 [%] less compared to calculated density. It seems unlikely that the given material and the thereby belonging material density is incorrect. This means that either the given geometry or the given mass of the CS1 Spacecraft is incorrect. The given geometry is specifically stated like the material thickness of the sphere as well as the diameter of the sphere and the tolerances. For the given mass it is not specifically stated whether it is only the mass of the CS1 Spacecraft or whether it is the mass of the CS1 Spacecraft including the so called CS1 Launching Cradle (cf. Figure 12). For now, it is assumed that the given mass is actually the mass of the CS1 Spacecraft and the CS1 Launching Cradle, in other words, the mother spacecraft. The mass of the CS1 Spacecraft is therefore set to calculated mass of 421,44 [g]. The tolerances are for convenience neglected. [57 73 74]

4.2 TRIPLE CALSPHERE EXPERIMENT

Intro – The Triple Calsphere Experiment (**TCE**) is developed by NRL in collaboration with the back then called Royal Aircraft Establishment (**RAE**). The RAE is a British Research Institute from the United Kingdom that is renamed in 1988 to the Royal Aerospace Establishment. The TCE exits, as its name already suggests, of three Calspheres that are known as Calsphere 3 (**CS3**), Calsphere 4 (**CS4**) and Calsphere 5 (**CS5**). They are launched together by the Thor Burner II Launch Vehicle as a piggyback of the **DMSP** (Defense Meteorological Satellite Program) 5A F3 Spacecraft on the 17th of February in 1971. [42 65 75 76]

Status – The launch vehicle managed to successfully insert the Triple Calsphere Experiment into an orbit around the Earth. The insertion orbit falls within the desired region of the atmosphere, namely the lower exosphere. In orbit, the three Calspheres are supposed to deploy in a predefined sequential time order so that they can be distinguished from each other through ground based radar observations. The deployment is assumed be successful since the Calspheres are identified from one another. The Orbital Parameters of the three Calspheres are observed until their reentry in the atmosphere of the Earth. It is therefore assumed that they stayed intact during their Orbital lifetime. The observations have proven to be useful for the intended studies. The Triple Calsphere Experiment is therefore assumed to be a successful mission. [65]

Application – One of the purposes of the Triple Calsphere Experiment is to validate Cook's Theorem. This is done by comparing the Drag Coefficient of CS5 with that of CS3 and CS4. Calsphere 5 differs only in

Figure 12: A Calsphere mounted in a Calsphere Cradle. [77]

surface material from CS3 and CS4. In case Cook's Theorem is right, the Drag Coefficient of CS5 is going to be different than that of CS3 and CS4. Since CS3 and CS4 are identical, their Drag Coefficient is expected to be the same. The Drag Coefficient of these Calspheres is determined by comparing the Orbital Parameters that are observed by NAVSPASUR. The remaining purposes are the same as that of the Dual Calsphere Experiment. The change in Semi-Major Axis is used again to determine the density at the orbital altitude of these Calspheres but then in a lower part of the lower exosphere. The density variations are used again to observe cyclic relations in Solar Activity. Each of these Calspheres serve also as Standard Targets for future use. They can calibrate the same type of radars as CS1 and CS2. In the meanwhile they can be used to determine several properties of existing ground based radars. They also provide the possibility for future optical systems to test if they can identify CS5 from CS3 and CS4. The Triple Calsphere Experiment is thus used for the same two applications as the Dual Calsphere Experiment, namely calibration and atmospheric research. [65]

Spacecraft – The payload of the CS3 Spacecraft is seen as the spacecraft itself. There are no subsystems onboard to support the payload. The CS3 Spacecraft is, as its name suggest, a spherical spacecraft. The diameter is given to be 26,04 [cm]. The mass is given to be 729,6 [g]. It is not stated if the mass includes the mass of the so called Support Structure in which the CS3 Spacecraft is placed during launch (cf. Figure 13). For now, it is assumed that the given mass is the mass of the CS3 Spacecraft. The last given feature is that the surface has a polished aluminum finish. The same calculations and observations apply for the CS4 and CS5 Spacecraft. The CS4 Spacecraft is identical to the CS3 Spacecraft. The CS5 Spacecraft is assumed to be basically the same as the CS3 and CS4 Spacecraft. The only difference is that it is gold plated and that it has a mass that is 0.4 [g] higher. For convenience it is assumed that this mass increase is due to the layer of gold applied on the exterior surface. The density of gold is 19,30 [g/cm^3]. This means that the volume used for the gold is about 0.0207 [cm^3]. The thickness of the gold is calculated to be about 0,194 [μm]. Because of the surface properties, the CS3 and the CS4 Spacecraft are often referred to as the Aluminum Calspheres. The CS5 Spacecraft is therefore often referred to as the Golden Calsphere. These alternative names caused sometimes confusion throughout the literature since it implies that the CS5 Spacecraft is made solely out of gold. [65] [73] [78]

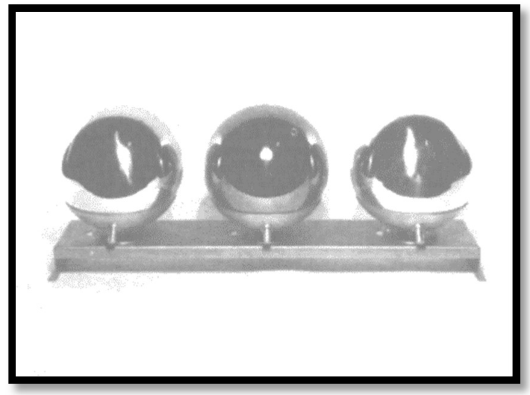

Figure 13: The Calspheres of the Triple Calsphere Experiment. The Calspheres on the sides seem to be the Calspheres with the polished aluminum finish (i.e. Calsphere 3 and Calsphere 4). The Calsphere in the middles seems to be the gold plated Calsphere (i.e. Calsphere 5). [65]

5

THE MYLAR BALLOON

Intro – During the 1960s, it became apparent to the US that space technologies needed to be developed rapidly. [79] In 1965, this need resulted in the establishment of the Space Experiment Support Program by the DOD, or simply said SESP. In 1971 this program was renamed to the Space Test Program (**STP**). [80] [81] For the sake of clarity, only the abbreviation STP is used. The STP was set up to accelerate the timely development of Space Technologies, by providing an on-orbit research and test capability. [80] Space Technologies could in this way be tested in space before they would be fully developed and deployed for operational use. [79] The three Calspheres from the Triple Calsphere Experiment for example were launched by the STP. The fourth type of SOKS, known as Mylar Balloon, was also launched by the STP, but then as part of the Gridsphere Drag Experiment. This experiment was a result of the ongoing research in so called Passive Communication Satellite, that started at the beginning of the 1950s. A passive communication satellite, or simply said, passive satellite, was defined as an orbiting reflector. In other words, it was a satellite that only reflects EMWs. A **Satellite** is defined here as a natural or artificial orbiting body. The Moon, for instance, could act as a Passive Communication Satellite. This was already the case for the Communication Moon Relay Project, that is also known as Operation Moon Bounce. [3] The term Passive Satellite is nowadays not only used to indicate orbiting reflectors. Because of its ambiguity this term is not used from here on. The term Passive Communication Satellite is neither used since it includes natural orbiting bodies. To excluded natural orbiting bodies, the term Passive Communication Spacecraft (**PCSC**) is preferred instead. For clearance, a **Passive Communication Spacecraft** is defined here as a Spacecraft that is used for communication purposes by reflecting Electromagnetic waves. A **Spacecraft** is defined here as an artificial (man-made) object that is designed for the space outside the atmosphere of the Earth. Spacecraft that are used for communication purposes by receiving and transmitting (modulated and or amplified) electromagnetic waves are, from here on, referred to as **Active Communication Spacecraft**. [3] [79] [80] [81] [82] [83]

Theory – Several concepts of Passive Communication Spacecraft were proposed at the beginning of the Space Age (cf. Figure 14). [84] The first successful Passive Communication Spacecraft was launched in 1960 and is usually known as Echo 1. [42] [85] Nowadays, it is also referred to as Echo 1A in case the failed attempt is considered as well. The successful Echo 1 Spacecraft was a Balloon Spacecraft with a surface made out of Mylar that had an aluminized skin and some internal subsystems. [86] [6] A **Balloon Spacecraft** is for convenience defined here as a spacecraft that is inflated in orbit in the form of a sphere. Nowadays, a Balloon Spacecraft may be better known as **Satelloon**. The next PCSC concept that was considered to be a success was West Ford 2. In that same year, **Syncom 2** was successfully launched and operated. This spacecraft was the first Active Communication Spacecraft that was launched in a Geosynchronous Orbit. Active Communication Spacecraft had eclipsed, thereafter, the efforts of subsequent attempts in achieving an operational communication system using Passive Communication Spacecraft. [6] Despite the success of Active Communication Spacecraft, the successor of the Echo 1 was launched in 1964, which is nowadays known as

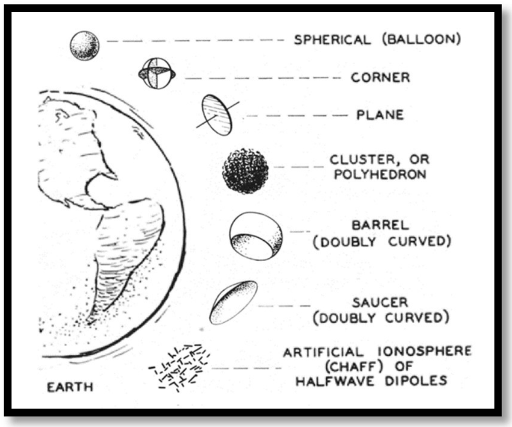

Figure 14: Concepts of Passive Communication Spacecraft. [84]

Figure 15: The Gridsphere Pascomsat after inflation.It is also known as OV1-8. [83 87]

Echo 2. [42 66] The Echo 2 Spacecraft was an improved version of the Echo 1 Spacecraft. One of the improvements was that Echo 2 managed to provide a smooth spherical spacecraft throughout its time in space. [6] Despite the improvements, the disadvantage of the large Area to Mass Ratio was not resolved. The large Area to Mass Ratio made the PCSC susceptible to SRP and Atmospheric Drag that caused the orbital lifetime to decrease significantly. [83] In an attempt to solve this problem, the Goodyear Aerospace Corporation came up with the concept of a spacecraft that was now known as Gridsphere. [6 42 66 83 84 85 86]

Concept – A **Gridsphere** was a Balloon Spacecraft with a grid surface made out of pentagonal and hexagonal wires that were each enclosed by a photolyzable film (cf. Figure 15). [87] A **wire** was in this case a thin flexible thread of metal. The **photolyzable film** was a thin sheet of plastic that would dissolve once it was exposed to Ultra Violet (**UV**) Waves. Once exposed in orbit to the UV Waves from the Sun, there would be nothing more than a spherical grid made out of pentagonal and hexagonal wires. The Area to Mass Ratio, in comparison to that of a hollow sphere of the same size, was significantly lower. It was therefore expected that a Gridsphere would be, in comparison, less susceptible to Solar Radiation Pressure and Atmospheric Drag, meaning, a longer orbital lifetime. [83] The lower Aero to Mass Ratio was expected to reduce also the probability of collisions with micrometeorites. A collision with a micrometeorite would be, in comparison, also less severe. The first ground tests showed that a Gridsphere acted as good as, or even better, in reflecting EMWs than a metalized sphere of the same size. [83] In other words, it was expected that a Gridsphere would cancel out the major deficiencies of the Echo Spacecraft. It was therefore launched in 1966 as a piggyback onboard of one of the Orbiting Vehicle 1 (**OV1**) Spacecraft. Even though this Gridsphere differed from the conventional spacecraft of the OV1 series, it was often referred to as OV1-8 (cf. Figure 15). Another name that was used was **PasComSat**, which stands for Passive Communication Satellite. The latter name is preferred and is therefore used from here on. The status of the Pascomsat mission was marked as a success. Despite the success, the actual increase in orbital lifetime with respect to a hollow aluminized sphere of the same size was not determined. This resulted in the proposal of another experiment that is nowadays known as the Gridsphere Drag Experiment (**GDE**). The proposed concept contained three Spacecraft of the same size (cf. Figure 16). [80] Two of these Spacecraft would be Gridspheres, and one of them would be a so called Mylar Balloon. A **Mylar Balloon** was nothing more than a Balloon Spacecraft made out of Aluminized Mylar. The two Gridspheres would have a wired grid with different **Mesh Dimensions**. The **Mesh Dimensions** were the dimensions of the pentagonal and hexagonal shapes that form the wire grid. They affect how the Gridsphere scatters EMWs at different frequencies. By comparing the scattering properties of each Gridsphere, it would be possible to determined how the Mesh Dimensions affect the scattering properties. The scattering properties of the Mylar Balloon would be compared with the Gridspheres so that the gain improvements of each Gridsphere could be determined. The Mylar Balloon would also be used to determine, in comparison, the increase in Orbital lifetime of each Gridsphere. It was also possible to use them for other studies. For instance, their orbital parameters could be used to determine the density at their orbital attitude. These parameters could also be used to determine the Atmospheric Drag, Charge Drag and the Drag Coefficient. [88] Hence, the term drag in the name of the experiment. Furthermore, it could possibly be used to determine at which altitude the free molecular flow transitions to laminar flow. [80] If needed, it would also be possible to use them for the calibration of Earth based Radio Wave radars. [89] This concept was selected by the STP and was therefore realized. [6 80 83 86 87 90 91 88 89 92 93]

Realization – In 1968, the STP launched the first GDE, which is here referred to as Gridsphere Drag Experiment 1 (**GDE1)**. The launch vehicle failed to place the GDE1 Spacecraft into orbit. Another attempt to launch GDE was provided by STP in 1971. The second attempt is, for convenience, referred to as Gridsphere Drag Experiment 2 (**GDE2**). Both experiments seem to be identical based on the given mission names for each launch. However, the information about GDE1 is scarce since the mission failed. The information obtained for GDE2, in particular about the application and spacecraft, are therefore assumed to be the same for GDE1. The Mylar Balloon of GDE2 (**MB2**), and therefore GDE1 (**MB1**), seems to have a mass below one kilogram. Both experiments are therefore considered to be SOKS Space Missions. [94 89]

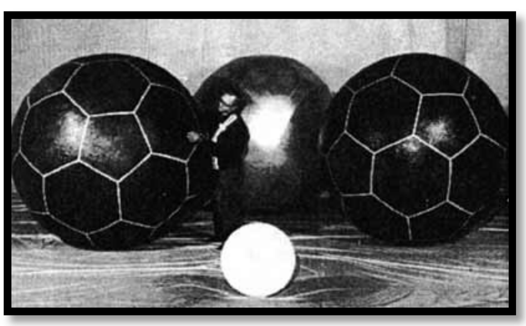

Figure 16: The three Spacecraft of the Gridsphere Drag Experiment 1 and 2. The two inflated Gridspheres (left and right) and the inflated Mylar Balloon (in the back) that are part of the Gridsphere Drag Experiment. The spacecraft in the front seems to be a Lincoln Calibration spheres. [95 80]

5.1 GRID SPHERE DRAG EXPERIMENT 1

Intro – On the 16th of August in 1968, GDE1 was launched as a piggyback by the Atlas SLV3 Launch Vehicle that had a Burner II Booster as upper stage. [80 81 89] This mission was developed by the Avionics Laboratory (**AVL**) with funding from USAF. The GDE1 Spacecraft are therefore also known as one of the spacecraft from the AVL-802 Experiment. The launch was provided through STP. [80 89] The flight number, assigned by the STP, was P68-1. [81 89] It is therefore also possible that GDE1 is considered to be part of this flight number. The spacecraft of GDE1 were launched together with several other spacecraft. The exact number is not known since the number of experiments was confused with the number of spacecraft. [96 88] A Multiple Orbit Insertion (**MOI**) was intended for the spacecraft on this launch. [80] The GDE1 Spacecraft were planned to be inserted in a circular polar orbit with an altitude of roughly 740 [km]. [80] The launch did not turn out to go as planned. None of the spacecraft were placed in an orbit due to a malfunction in the upper stage of the Launch Vehicle. The **Fairing**, which is the conical shell structure at the nose-top of a launch vehicle, failed to separate from the booster with the spacecraft. GDE1 was, thus, unsuccessful. [89 88 97 98] The purpose of GDE1 was to determine, through the MB1, the aerodynamic characteristics of both GDE1 Gridspheres. [88] The atmospheric drag was also intended to be determined through the orbital elements of each GDE1 Spacecraft. [80] Further specific details, for instance, about MB1, were not available. [80 81 96 89 88 97 98]

5.2 GRID SPHERE DRAG EXPERIMENT 2

Intro – Gridsphere Drag Experiment 2 was launched on the 7th of August in 1971. An Atlas F Launch Vehicle, with a Dual OV1 configuration, was used for this launch. [80 81 42] AVL remained the developer of GDE2 and was again funded by USAF. These spacecraft were also considered to be part of the AVL-802 Experiment, and resulted therefore in the assumption that GDE1 was the same as GDE2. [80 89] The flight number, assigned by STP, was P70-2. [80 81] The GDE2 Spacecraft were attached to the apogee kick motor of the OV1-21 Spacecraft. [80] The OV1-21 Spacecraft was, together with OV1-20 Spacecraft, the primary payload of the Atlas F launch vehicle. The names of these spacecraft show similarities to that of Pascomsat (OV1-8), however, they are completely different. [80] Together, they functioned also as the upper stage of the Launch Vehicle, and carried each a number of smaller spacecraft. [80] The GDE2 Spacecraft were, thus, launched as a piggyback. A **MOI** was also scheduled for this launch. [80] The intended orbit for the GDE2 Spacecraft was similar to the intended orbit of the GDE1 Spacecraft. [80 42] This time, however, the orbit injection went as planned. [80 81 89 42]

Status – The GDE2 Spacecraft were successfully placed into their orbits. [94] The mission itself was stated to be successful. [81] However, it is not clear whether MB2 was successful too. It was stated that one of the Gridspheres of GDE2 was not operational. On the other hand, it was expected that MB2 would have, in comparison, an orbital lifetime that was several years less. Nevertheless, the operational and orbital lifetime of the remaining two GDE2 Spacecraft were in the same order of years. [81 99 80] MB2 could, therefore, also be the spacecraft that failed. [80 81 94 99]

Application – The main application for GDE2 was the same as described for GDE1. The GDE2 Spacecraft were mainly used to determine the difference in atmospheric drag between them. They were also used to determine the atmospheric density at their orbital altitudes. In other words, the orbital dynamics of each of these spacecraft was studied again. The objective to use them as a target for calibration of Earth based Radars, was not applied. [80 89 76]

Spacecraft – The payload of the Mylar Balloon 2 Spacecraft is seen as the inflated spacecraft itself. It is assumed that it has no subsystems. After inflation, the Mylar Balloon 2 Spacecraft is assumed to have the form of a sphere. The mass and diameter of this sphere is believed to be respectively about 907,2 [g] (2 [lb]) [100] and 213,4 [cm] (7 [ft]) [42 80]. It is furthermore believed that the Mylar Balloon 2 Spacecraft is made out of Aluminized Mylar. Aluminized Mylar is nothing more than a Film made out of Mylar that is covered on both sides by a Foil made out of Aluminum. A **Film** is defined here as a thin sheet of plastic and a **Foil** is defined here as a thin sheet of metal. In other words, the skin of the Mylar Balloon 2 Spacecraft is a **Metalized Film**. The material thickness of each of these layers is not given though. Another Balloon Spacecraft that had a skin made out of aluminized Mylar was the Echo II Spacecraft. The skin of the Echo II Spacecraft was made out of a 0,35 [mil] (about 8,89 [μm]) thick Mylar film that was covered on both sides by a 0,18 [mil] (about 4,572 [μm]) thick aluminum foil. [86] In case the same material thickness is assumed for the Mylar Balloon 2 Spacecraft, the mass is calculated to be about 264,26 [g]. For the calculated mass a density of 2,70 [g/cm^3] and 1,38 [g/cm^3] is used for respectively Aluminum and Mylar. The calculated mass is about 29,13 [%] of the given mass. Assuming the ratio between the layers remains the same, the layers for the Mylar Balloon 2 Spacecraft must be increased by a factor of 3,4. In other words, for the given mass, the layer thickness is estimated to be about 240 [%] bigger than that of the Echo 2 Spacecraft, which is remarkable. An explanation could be that the given mass is actually the mass of the Mylar Balloon 2 Mother Spacecraft, which includes for example the Deployment System as well as the Mylar Balloon itself. [42 80 86 100]

6

THE ORBITAL DEBRIS RADAR CALIBRATION SPHERES

Realization – Three attempts are made to realize the ODERACS Experiment (cf. Figure 17). The first attempt in 1992 was not successfully realized. The second attempt of the same ODERACS Experiment, in 1994, did succeed. The third attempt, that differed from the first two attempts, was successfully realized in 1995. The three attempts are referred throughout the literature in different ways. The first attempt is referred to as ODERACS or ODERACS 1. The second attempt is also referred to as ODERACS and ODERACS 1 but also as ODERACS 1R. The third attempt is referred to as ODERACS 2 and ODERACS II next to ODERACS. To make a clear distinction between them, the first, second and third realization are referred from hereon as **ODERACS 0** (**OD0**), **ODERACS 1** (**OD1**) and **ODERACS 2** (**OD2**). The ODERACS acronym, for all three attempts, differs in literature as well. It either stands for Orbital DEbris RAdar Calibration Spheres, which is commonly used, or Orbital DEbris RAdar Calibration System. ODERACS 2 used next to spheres also dipoles. The latter meaning is applicable to all the ODERACS missions, the first definition is actually only applicable to OD0 and OD2. The **ODERACS** Acronym that is used here is therefore set to Orbital DEbris RAdar Calibration System. [101] [102] [103] [104] [105]

6.1 ODERACS 0

Intro – The back then called Space Science Branch (**SSB**) of the Johnson Space Center (**JSC**) developed OD0 in collaboration with NCSU (North Carolina State University) with funding of the National Aeronautics and Space Administration (**NASA**). [106] [107] ODERACS 0 is launched on the 2nd of December in 1992 by the Space Shuttle as a secondary payload onboard the Orbiter Vehicle (**OV**) Discovery as part of the Space Shuttle Mission STS-53. [106] [108] The abbreviation **STS** stands for Space Transportation System and is the initial name of the Space Shuttle Program. Onboard this flight, the ODERACS 0 is stored in a Get Away Special (**GAS**) Canister with a Motorized Door Assembly (**MDA**) that is provided by the Hitchhiker (**HH**) Program. The HH Program is developed and operated by the Goddard Space Flight Center as part of their Shuttle Small Payloads Project. This project is set up to make full use of the payload capabilities of the Space Shuttle and provide access to space at relatively low cost for everyone of interest. [109] [110] The GAS Canister of OD-0 is placed in the Cargo Bay of the Space shuttle together with another secondary payload known as Cryogenic Heat Pipe Experiment and a classified main payload of the DOD. [108] After the launched, the crew members on this flight are instructed to open the MDA of the OD-0 Gas Canister on command. Once the MDA is opened OD-0 is responsible for deploying six OD-0 Spacecraft. The deployment is done by their own designed system. This deployment system is referred to as the Orbiter Ejector. It is also used to store the six OD-6 spacecraft until deployment. [111] From these six spacecraft, only two of these spacecraft have a mass below 1 [kg] and are considered to be SOKS. The planned sequence of events for the OD-0 did eventually not turn out as planned.[106] [109] [108] [107] [110] [111]

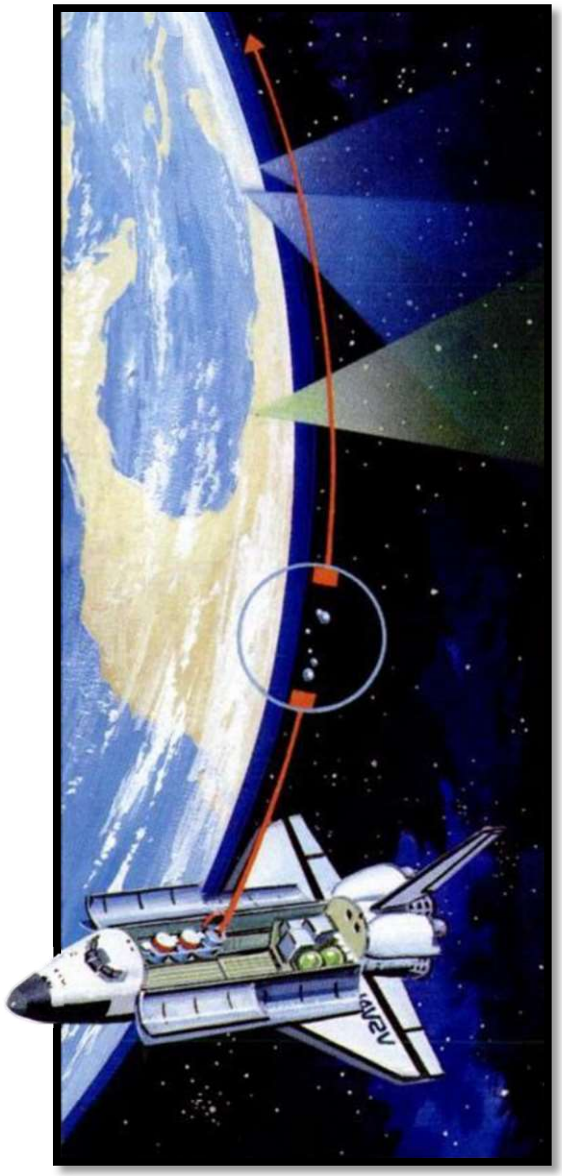

Figure 17: An artist impression of the mission concept of ODERACS. The ODERACS Spacecraft are deployed from a Canister onboard the space shuttle. They were intended for the calibration of Earth based ground stations that detect, track, and identify Earth orbiting objects. The capabilities of these stations could also be determined through these Spacecraft. The artist impression applies to ODERACS 0 and ODERACS 1, since three different pairs, with each two spheres of the same size, were deployed. For ODERACS 2, six spacecraft were deployed as well, of which one sphere of each of these pairs was identical. The remaining spheres of each pair were replaced by three needles, of which two identical. [112]

Status – Opening the MDA of the OD0 GAS Canister on command is scheduled for the third Flight Day (**FD**) of the OV. Before opening the MDA, the Cargo Bay Doors are opened first. Secondly, the outward normal vector of the OV is aligned with its velocity vector. This alignment is done to prevent a collision between the OV and the OD0 Spacecraft after deployment. [111] After that, Camera C, which is a **CCTV** (Closed Circuit Television) that is placed at the back of the Cargo Bay, is turned on [113]. This is done to visually confirm the deployment of the OD0 Spacecraft and to determine for each of these Spacecraft the deployment velocity. The deployment velocity is of importance for the prediction of the orbital trajectories of each sphere. [105] Once the camera is turned on, one of the assigned crew members receives a command from the operation center to turn on a switch that opens the MDA. After the MDA is opened the Orbiter Ejector of OD0 spacecraft is activated and the OD0 Spacecraft are deployed. To decrease the chance of collision between the OD0 Spacecraft the OD0 Spacecraft are deployed one by one within 2 minutes. [111] After the deployment, the same crew member is assigned to close the MDA of the OD0 GAS Canister. As is known now, the OD0 Spacecraft did not deploy despite the fact that the Space Shuttle launched the OV Discovery successfully into orbit. In preparation of OD0, it seemed that Camera C did not work properly. As a solution Camera C is substituted by Camera B, which is another CCTV camera placed in the back of the Cargo Bay. [113] Ten minutes before opening the MDA, the operating crew member reported that the obtained signals during checkup are not as expected. Before a solution is found the 20 minutes working window passed and operations for the OD0 are ceased. The next opportunity is set to the 5th FD but on the 4th FD the ground controllers decided to not do another attempt. From the ground analysis it seemed that a dead battery is most likely the cause for the bad signal. [114] An Extravehicular Activity to check and recover the battery is considered but is not worked out due to time constraints. After the return of the OV back to Earth it is confirmed that a dead battery prevented the MDA to open. [108] The failed deployment of the OD0 is therefore seen as a launch vehicle failure since the launch vehicle failed to supply the promised services. [106] The status of the OD0 is thus set to failure. [105] [106] [108] [111] [113] [114]

Spacecraft – The two OD0 Spacecraft that are considered to be SOKS have each a given mass of about 0,531 [kg] (1,17 [lb]). [105] They are both solid spheres with a diameter of roughly 5,08 [cm] (2 [in]) and are made out of Stainless Steel. [78] [105] **Stainless Steel** is nothing more than an Iron Alloy. The density depends on the type of Stainless Steel. Based on the given information, the density is calculated to be 7,73 [g/cm^3] and is well within range in comparison to other existing densities of Stainless Steel. The given mass is therefore assumed to be correct. The only difference between both SOKS is the surface finish. One of them is highly polished while the other one is sand blasted. It is given that these spacecraft are scheduled to be ejected as the 3rd and 4th OD0 Spacecraft but which one goes first is not stated. [111] Based on the launching sequence of the OD1, it is assumed that the polished sphere is scheduled to be the third OD0 Spacecraft to be deployed and the sand blasted the fourth. For convenience they are referred from here on as respectively **OD0-C** and **OD0-D**. The payload of each of these spacecraft is seen as the spacecraft itself. They have therefore no subsystems. [78] [105] [107] [111]

6.2 ODERACS 1

Intro – ODERACS 0 is not released from the GAS Canister and returned back to Earth with the OV of STS-53. At that time, experiments placed in a GAS Canister are accessible within two to three weeks after landing. [110] It is therefore assumed that ODERACS 0 is picked up by the Space Science Branch at JSC and it is believed that OD0 is reused again for OD1. [101] [115] This mission was launched on the 3rd of February in 1994 by the Space Shuttle as a secondary payload onboard the OV Discovery but this time as part of the Space Shuttle Mission STS-60. [115] It is stored again in a GAS Canister with a MDA that is provided by the HH Program. The OD-1 GAS Canister is attached this time to a GAS Bridge to which more GAS Canisters are attached that contain other secondary payloads like BremSat [115]. The GAS Bridge is placed in the aft section of the Cargo Bay that contains two more primary payloads (Wake Shield Facility 2 and Spacehab 2). [116] The planned sequence of events is similar to that of OD0. Two out of the six OD1 Spacecraft are SOKS. This time everything went as planned. [101] [110] [115] [116]

Status – The deployment of the OD1 Spacecraft took place on the 9th of February in 1994 during the 7th Flight Day. [115] [117] The CCTV Camera C of the OV recorded the deployment. The 3rd and 4th deployed Spacecraft are the SOKS. The recordings showed no anomalies during deployment and are used to calculate the deployment velocities. [117] After the deployment, the OD1 Spacecraft are detected by ground based radar and optical stations worldwide and used for their intended purposes. [118] [119] OD1 is thus successfully accomplished. [115] [118] [117] [119]

Spacecraft – The two OD1 Spacecraft that are considered to be SOKS are the third and fourth deployed OD1 Spacecraft. [117] [120] For convenience they are referred to as **OD1-C** and **OD1-D**. [120] [121] [122] They are the same as OD0-C and OD0-D which makes it plausible that they are reused again for OD1. Thus they are both solid spheres with a diameter of roughly 5,08 [cm] (2 [in]), are made out of Stainless Steel, and have a given mass of about 0,531 [kg]. [101] [117] [120] [121] [123] The given mass is again assumed to be correct for the same reason as for OD0. OD1-C has a highly polished surface (cf. Figure 18) with an estimated albedo and scattering of respectively 0,56, and 0,07. [101] [112] OD1-D has a sand blasted surface (cf. Figure 19) with an estimated albedo and scattering of respectively 0,38 and 0,40. [101] The payload of each of these spacecraft is seen as the spacecraft itself. They have therefore no subsystems. [101] [112] [117] [120] [121] [123] [122]

6.3 ODERACS 2

Intro – OD2 is the successor of OD1. The difference between them are the Spacecraft that belong to these experiments. OD1 contains six spherical spacecraft while OD2 contains three Spherical and three Dipole Needle Spacecraft. One of these spheres and the three Dipole Needles have a mass less than 1 [kg]. OD2 contains therefore four SOKS instead of two like OD1 and OD0. [124] ODERACS 2 is launched exactly one year after OD1, namely on the 3rd of February in 1995. It is launched by the Space Shuttle as a secondary payload onboard the OV Discovery as part of the Space Shuttle Mission STS-63. It is stored also in a GAS Canister with a MDA that is provided by the HH Program. [104] The OD-2 GAS Canister is also attached to a GAS Bridge that contains more GAS Canisters with other secondary payloads like the Cryogenic Systems Experiment and Shuttle Glo-2 Experiment. [125] The GAS Bridge is placed in the aft section of the Cargo Bay that contained two more primary payloads known as SPARTAN-204 (Shuttle Pointed Autonomous Research Tool for Astronomy) and Spacehab 3. [104] [125] The same sequence of events for deploying the OD2-Sapcecraft is applied as for OD1 and OD0. Everything went again as planned. [104] [125] [124]

Status – The deployment of the OD2 Spacecraft took place during the 2nd Flight Day on the 4th of February in 1995. [104] The deployment of the OD2 Spacecraft were initially scheduled for deployment for the 1st FD. They are deployed on the 2nd FD though due to better elevation angles of the OD2 Spacecraft with respect to the main ground stations. [104] [125] All the OD2 Spacecraft are deployed within a time span of 152 [s]. [104] The deployment is again recorded by a CCTV onboard the OV, but this time Camera B is used. The Image Science and Analysis Group used these recordings to provide to the SSB the deployment velocities of each OD2 Spacecraft. The SSB was at that time already known as NASA's ODB (Orbital Debris Office) Office. [124] In addition, another CCTV Camera is used for OD2, namely Camera D. Camera D is placed on the top of Flight Deck and provides the view of the OD2 Space craft right after the deployment. [113] [124] The Image Science and Analysis Group provided the rotation rates of the Dipole Needles based on these recording. The rotation rates were determined by analyzing the so called blinking rate, which was in this case the rate at which Sunlight was reflected by the dipoles. The recordings showed furthermore no anomalies during deployment. The OD2 Spacecraft that are considered to be SOKS are the 2nd, 3rd, 4th and 6th deployed Spacecraft. [124] Five of the OD2 Spacecraft are detected by Ground Based radar and optical stations that are stationed worldwide and are used for their intended purposes. OD2 is therefore seen as a successful mission. [104 113 124 125]

Spacecraft – The four OD2 Spacecraft that are considered to be SOKS are the second, third, fourth and sixth deployed OD2 Spacecraft. [124] For convenience these spacecraft are referred to as respectively **OD2-B**, **OD2-C**, **OD2-D** and **OD2-F**. OD2-C is a polished stainless steel solid sphere with a diameter of roughly 5,08 [cm] (2 [in]) and a mass of about 0,531 [kg]. [123 124 125 126 127] In other words, it is the same spacecraft as OD1-C and OD0-C. The remaining SOKS are Dipole Needle Spacecraft. Two of these Dipole Needle Spacecraft were identical, namely OD2-B and OD2-F. [126] [127] They are made out of a Platinum Iridium alloy, have a given length of about 13,35 [cm] (5,255 [in]) [124 125], and a given diameter of roughly 1,016 [mm] (0,040 [in]). [125] The mass of each of these Dipoles is given to be about 1,5 [g]. [123] [126] Just like with the West Ford Needles, the form of each dipole is assumed to be a cylinder. The calculated mass is about 2,33 [g] using a density of 21,5 [g/cm^3] for Platinum Iridium. This is about 55 perdent more than the given value. It has a length of

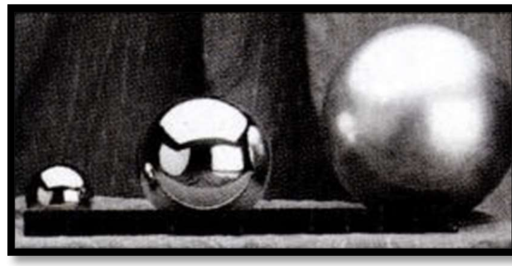

Figure 18: Three of the six ODERACS 1 Spacecraft. The 2 inch polished stainless steel solid sphere on the left is the ODERACS 1 C Sphere. The 4-inch sphere in the middle is also a polished stainless steel solid sphere. The 6-inch sphere on the right is a sand blasted aluminum solid sphere. [112]

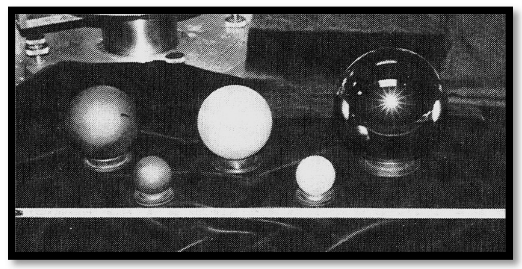

Figure 19: The test spheres of ODERACS 1. They are used to determine their optical properties. The 4 and a 2 inch spheres on the left are sand blasted blackened stainless steel solid spheres. The 4 and 2 inch spheres in the middle are sand blasted stainless steel solid sphere. The 6-inch sphere on the right is a polished chrome plated aluminum solid sphere. It is believed that the three spheres on the right are part of the actual flight spheres of ODERACS 1. In that case the 2-inch sphere in the middle is the ODERACS 1 D Spacecraft. [101]

roughly 4,42 [cm] (1,740 [in]) [124 125] and a given mass of 0,5 [g]. [123] [126] The remaining properties like the diameter are the same as the other two Dipole Needles. The calculated mass is 0,77 [kg] using the aforementioned density for Platinum Iridium. This is about 54 [%] more than the given value. Thus, both calculated masses are about 55 [%] higher than the given mass. In case the given masses are assumed to be correct the material density needs to be about 13,9 [g/cm^3]. The given material might therefore be different than the actual material of the Dipole Needle Spacecraft. For all four of these spacecraft the payload is assumed to be the spacecraft itself. They have therefore also no subsystems. [125 124 126 123 127]

7

THE PICO SATELLITE OF OPAL AND MIGHTYSAT

Intro – The advancements of miniaturized electronics in the 1990s came along with new possibilities. One of these outcomes was the so called Satellite Quick Research Testbed (**SQUIRT**) Program. The SQUIT Program was already setup in 1994 by the Satellite Systems Development Laboratory (**SSDL**), that was also just installed at that time, but then by the Department of Aeronautics and Astronautics of Stanford University. It was an educational program for Bachelor, Master, and or PhD students that was setup to facilitate hands on experience with the design and operation of a Spacecraft. This was done by letting them design and manufacture systems of a Spacecraft that would actually be built. One of them is known nowadays as **OPAL**, which stands for Orbiting Picosatellite Automated Launcher. OPAL was the second Spacecraft developed as part of the SQUIRT Program. At the time of development, the magnetic field was, up till then, only measured by magnetometers onboard bigger sized spacecraft. In situ measurements were done over the course of time while the Spacecraft were orbiting the Earth. By adding all the measurements together, it was possible to obtain an overview of the global magnetic field. Although several new insights were obtained, there was still a desire among researchers to observe the magnetic field in more detail. The issue was that each measurement was done at a different time, while ideally, a global measurement at different points, yet, at the same time, was desired. Another point of discussion was the size of the spacecraft themselves. They could have caused a local disturbance in the magnetic field. However, it was not possible to measure any of these local disturbances since another spacecraft was required that would measure the magnetic field in close vicinity, at the same time. This need resulted in the proposal of OPAL. The solution to the aforementioned need, as well as the initial concept of OPAL, is actually provided in the OPAL's abbreviation. The main idea of one of the initial concepts was to deploy several magnetometer spacecraft in an automated way, that would, thereafter, orbit in close vicinity around OPAL. For another initial concept, the SOKS were intended to be hockey puck sized Spacecraft with magnetometers (cf. Figure 20). They would each measure the magnetic field at the same time that OPAL would do this. Thereafter, they would transmit their Telemetry to OPAL, who would on its own turn, transmit its own telemetry, together with the received telemetry of the magnetometers. In this way, it would be possible to determine if bigger sized Spacecraft cause local disturbances that might affect their measurements of the magnetic field. In addition, it would also be possible to create a local 3D map of the Magnetic field. [128] [129] [130] [131] [132] [133] [134] [135] [136]

Realization – Although the initial concept was developed for several years, the deployment system turned out to be too complex, and was eventually cancelled. This cancellation resulted, however, in four other SSMs that were launched through OPAL by the Minotaur-1 on the 27th of January, 2017. Although they shared the same launch, they are considered to be independent SSMs since they did not work together as a Distributed Space System (**DSS**), as was the case for the initial concept. There were three deployment trays onboard OPAL that had each two deployment slots in which either two or one bigger sized OPAL PicoSat could fit. In total, there were two bigger sized OPAL PicoSat that formed one SSM, namely Thelma and Louise. Although part of the same project, a smaller sized OPAL PicoSat, named JAK, is considered as another SSM since it was not part of Thelma and Louise. JAK shared the same deployment slot with another smaller sized OPAL PicoSat known as StenSat. This is the third SSMs of OPAL. The last slot, contained also two smaller sized OPAL PicoSat, but since they were tethered to one another and form one Spacecraft together, they are considered to be, together, the last SSM of OPAL. They are referred for convenience as the Tethered Aerospace Corporation Spacecraft, or TACS. Their names in literature vary from DARPA PicoSat to Picosat 1 to 9, as well as the Aerospace Corporation Picosat. The successor of this SSMs was launched through MightySat II.1 in the same year.

Figure 20: The initial concept of OPAL. The acronym of OPAL, Orbiting Picosatellite Automated Launcher, seems to refer to this concept. [136]

7.1 STENSAT

Intro StenSat is built by three so called radio amateurs that are part of the Radio Amateur Satellite Corporation (**AMSAT**) in North America (**NA**) (also known as **AMSAT-NA**). [137] [138] [139] It all started after AMSAT-NA send out an e-mail to their members in November 1998. This e-mail presented an opportunity to launch a Sub One Kilogram Spacecraft through the OPAL program. Three of the AMSAT-NA members decided to apply and got selected about a month later. This left them with four more months to design their Spacecraft which is nowadays known as StenSat. [138] StenSat is named after a farmhouse called Stenhouse since at one point at a time the three radio amateurs shared this house. [138] The Spacecraft name stands presumably thus for Stenhouse Satellite (cf. Figure 21). [137] [138] [139] [140]

Status – On the 11th of February, 2000, at 01:59:13 Coordinated Universal Time (**UTC**), OPAL successfully deployed StenSat together with JAK. In the Pacific Standard Time (**PST**) both spacecraft are deployed on the 10th of February of 2000, around 6 O'clock in the afternoon. [141] [137] The planned sequence of events after the deployment are as follows. First, the stowed antennas are deployed by melting a fishing wire after the batteries are fully charged. Thereafter, Telemetry is transmitted once every 5 seconds until a command is received from the main ground station to do this every 120 seconds. Next to the Telemetry, a Morse code ID is send every 240 seconds. [141] In addition, StenSat transmits a so called PING after receiving a command from one of the ground stations to do so. Unfortunately, none of the ground stations received any signal from StenSat which resulted in a failed mission. A cause for this failure is not known. [141] [137] [142] [139]

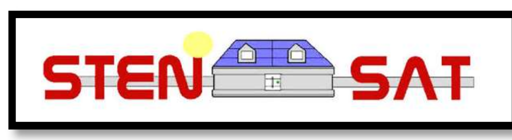

Figure 21: The StenSat Logo. The Stenhouse is implemented in the logo of StenSat. It represents the deployed version of the StenSat Spacecraft. Two of the four antennas are clearly seen behind the StenSat letters. Another antenna is shown by the vertical stripe in the 'Door' of the Stenhouse. There is another antenna that cannot be seen in the StenSat Logo. This antenna is placed at the back of the Stenhouse in the opposite direction of the antenna placed at the door. The windows placed on top of the StenSat Spacecraft might be a representation of the installed Sun Sensors which are not clearly shown in the real design of the StenSat Spacecraft. [140]

Application – StenSat is not only build by Radio Amateurs, it is also intended for Radio Amateurs around the world. [141] [137] **Radio Amateurs**, often referred to as **HAM**s, are Amateur Radio Operators. **Amateur Radio** is nothing more than non-commercial communication through EMWs that have a frequency that falls within the frequency range for Radio Amateurs allocated by the ITU (International Telecommunication Union). It is available for everyone who is interested in setting up their own ground station to communicate for example with other HAMs by means of a spacecraft or gain experience in communicating with spacecraft. Spacecraft that are built by Radio Amateurs and are intended for Radio Amateurs are also known as **Amateur Radio Satellite (ARS)**. It is common that AMSAT gives a so called OSCAR designation and number once an ARS is successful. The abbreviation **OSCAR** stands for Orbiting Satellite Carrying Amateur Radio. OPAL, for example, is a successful ARS and is therefore referred by Radio Amateurs as OSCAR-38. StenSat did not receive an OSCAR designation and number most likely because the mission failed. The idea of StenSat is to let Radio Amateurs send voice messages to other Radio Amateurs all around the world. This is possible through a **FM** (Frequency Modulation) Voice Repeater onboard StenSat. [141] [137] A **Repeater** does basically nothing more than receive EMWs with a certain frequency that are send from Earth, and transmit it back to Earth again on the same or a different frequency. Next to exchanging FM voice messages, Radio Amateurs have the possibility to "Ping" StenSat by transmitting a predefined command. [141] Although "Pinging" StenSat is not defined, it is assumed that "**Pinging**" means to let StenSat transmit a beeping sound on command. While in orbit, the idea of StenSat is also to let it broadcast its Household Data through Amateur Radio. [141] [139] In this way, Radio Amateurs are able to obtain data from StenSat. The Application of StenSat is therefore set to communication as well as education since everyone who has interest can interact with StenSat and get more experience with Amateur Radio. [141] [137] [139]

Spacecraft – The main structure of the StenSat Spacecraft consists of a metal Chassis that is basically a hollow cuboid. The Chassis is enclosed on both ends by a Circuit Board (**CB**). The exterior of these CBs are covered by solar cells for the Power System. (cf. Figure 22). [141] [137] Inside the StenSat Spacecraft two more CBs are placed. One CB used mainly for the data handling system while the other one is used mainly for

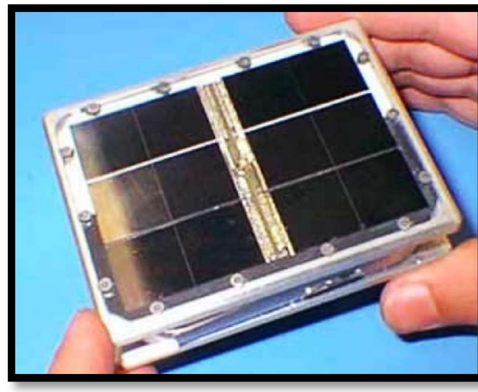

Figure 22: The StenSat Spacecraft in stowed position. The Antennas are placed in the cutout around the circumference of the StenSat Spacecraft. The metal frame is the Chassis. The top end is enclosed by a Circuit Board that has Solar Cells on its exterior. [141]

the Payload. They also contain components of the Power System and Attitude Determination and Control System. The mass of the StenSat Spacecraft is given to be 232,47 [g]. [141]

7.2 THELMA & LOUISE

Spacecraft – The Thelma and Louise Spacecraft are seen as Identical Spacecraft (cf. Figure 23). For convenience both spacecraft are referred to as the **TNL** (Thelma and Louise) Spacecraft. Their payload is supported by five subsystems, namely the Structure System, Power System, Communication System, Onboard Data Handling, and Attitude Determination and Control System. The antennas are deployed in orbit (cf. Figure 24).

Figure 23: The Thelma and Louise Spacecraft in stowed positions. The Antenna of the Communication System is placed between the Solar Panels. The black cuboid on the right contains the Payload Antenna. [143]

Figure 24: The antennas of the Thelma and Louise Spacecraft in deployed position. The antenna on the top is part of the Communication System. The lower antenna is part of the Payload. [143]

7.3 JAK

Intro – Another SOKS is believed to be made by the Artemis Team is JAK. The letters J, A and K are the initials of the infant son of the advisor of Artemis. JAK is often interchangeably used with MASat 1 or MASat, which seemed to stand for Miniature Amateur Satellite. [126] It is in literature often mistakenly seen as either an alternative name of JAK, or as another SOKS that was deployed from OPAL. [126 144 145]

7.4 TACS 1

Intro – In 1998, one of the employees at Aerospace Corporation coordinated the support between USAF's STP, the Air Force Research Laboratory, the Air Force Office of Scientific Research and the Defense Advanced Research Projects Agency (**DARPA**), to launch OPAL on the first flight of the Minotaur Launch Vehicle that is part of the Orbital Suborbital Program. [146 147] In return, Stanford University provided one of the six Deployment Bays to The Aerospace Corporation. [146] The Aerospace Corporation is a Federally Funded Research and Development Center that develops spacecraft for military purposes. [148] An internal team within Aerospace Corporation, that is known as the El Segundo Team and consists of 14 experts, realized in the end, in commission of DARPA's Microsystems Technology Office that provides the funding, two identical SOKS that contain hardware developed by the Rockwell Science Center. Each of these SOKS has in addition a tether of the same length of which the ends are connected to each other through a Tether Connector. [149 146 150 148] Together, they form a tethered spacecraft (cf. Figure 25) and are considered here as one SOKS that is for convenience referred to as the Tethered Aerospace Corporation Spacecraft (**TACS**) 1. Each individual SOKS of TACS 1 is referred to as the Aerospace Corporation 1 (**AC1**) Spacecraft. The idea is to eject TACS 1 from OPAL on command. [149] The deployment of the tether is initiated during the ejection because the AC1 Spacecraft, which are in stowed position pressed with their Tether Sides against one another, push each other away with their compressed Separation Spring. [148 150] The power of each AC1 Spacecraft is also turned on during the ejection, presumably, by their released Separation Spring. [148 150] Thereafter, both AC1 Spacecraft are put into a so called Beacon State where they continuously transmit their Tracking Signal until they receive a Telecommand with other instructions. [149] A **Tracking Signal** is defined here as EMWs that are transmitted for tracking purposes. The Telecommands are send by a primary ground station that uses theses tracking signals to establish a Communication Link with each AC1 Spacecraft. Tracking a Spacecraft through their Tracking Signal is known as **Active Tracking**. [149] The Active Tracking is in this case only possible when the primary ground station points its high gain narrow beamwidth antenna towards the weak Tracking Signals of TACS 1. [146] Additional ground stations are therefore used first to detect and track TACS 1 so that the antenna of the primary station is pointed towards

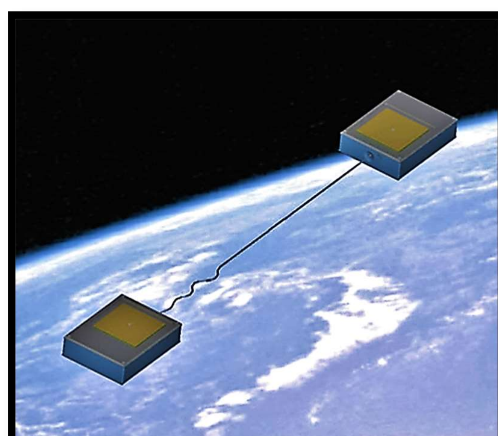

Figure 25: A rendering of the Tethered Aerospace Corporation Spacecraft 1. [148]

the right direction at the right time. [146] These additional ground stations do not make use of the Tracking Signal and is therefore also known as **Passive Tracking**. [149] In addition, the ejection command is transmitted at a time that OPAL is within view of these ground station to facilitate the initial Communication Link with TACS 1. [149] After the establishment of the Communication Links, both AC1 Spacecraft are instructed what to do, either as individual SOKS or as an Interconnected Distributed Space System (**IDSS**), until they ran out of battery. As is known now, not everything turns out to go as planned. [150] [148] [149] [146] [147]

Status – TACS 1 is successfully ejected from OPAL on the seventh of February in 2000 at 03:34:16 **UTC** (06-02-2000, 19:34:16 PST). [137] [146] A successful Communication Link between the Primary Ground Station and TACS 1 is established a day after the ejection, although it is initially planned to establish this right after ejection. A major portion of the battery is therefore, unintentionally, used for the Beacon State. [149] It seems that the passive tracking capabilities of OPAL's main station at Stanford is used before and after the ejection of TACS 1 and that this effort is insufficient to point the Primary Ground Station towards TACS 1 due to a margin of error in the Orbital Elements. In reaction to that, the Aerospace Corporation applied a novel spiral tracking method to locate TACS 1 with the primary ground station in addition to the use of another passive tracking ground station. [151] [146] It is not possible to establish a Communication Link with TACS 1 if both of the Separation Springs are not released since they initiate the deployment of the tether and turn on the power of the AC1 Spacecraft. It is therefore assumed that the Separation Springs are successfully released. After the established Communication Link, a number of ground breaking transmissions is exchanged between the AC1 Spacecraft and the Ground Station. At the 10th of February in 2000, the contact is lost because the batteries are exhausted, which is more than two weeks earlier than expected. [149] It seems that the AC1 Spacecraft are therefore not used as an IDSS even though it is stated that a communication link between these SOKS is established. [137] [149] Nevertheless, TACS 1 is stated to be a success since valuable data is obtained. [137] [149] [151] [146]

7.5 TACS 2

Intro – TACS 2 is basically the same as TACS 1. The main difference is that it was launched with MightySat II.1. To not interfere with this Spacecraft, more than a year passed by before it was deployed. This was considered to be part of the mission of TACS 2 and determine if it was possible the Spacecraft would still work after a year. The Deployment went successful. Although minor improvements were made, TACS 2 did not turn out to be a success as TACS 1.

8

THE CHIP SIZED SPRITE SPACECRAFT

Intro – The end of the 1990s and the start of the Millennium was marked by the rapid advancements of affordable miniaturized consumer electronics that were made out of Commercial of the Shelf (**COTS**) components. [152] These developments contributed to the earlier discussed OPAL and MightySat 2.1 SOKS. These missions resulted in the CubeSat program that has become a big success in the space industry. The success of the CubeSat program led also to a boost in publications of SOKS concepts and mission concepts with SOKS. Some of these SOKS concepts were part of the Sprite Project. This project resulted in the launch of two SOKS Space Missions. They were both driven by the need to reduce the costs of space missions, and the desire to make the space industry accessible to everyone. [152]

Theory –The Sprite Project was initiated at Cornell University in 2005. The initial aim of this project was to develop a Miniaturized Spacecraft with affordable COTS components on, preferably, a centimeter squared Integrated Circuit (**IC**). [153] [154] This miniaturized spacecraft, for convenience referred to as **IC Sprite**, should contain all the basic subsystems to support a payload with a set of specific applications. (cf. Figure 26). [153] [155] In other words, the intentions were similar to that of the TRS, namely developing a GUS, but this time, as small and cheap as possible. The design of this miniaturized spacecraft wa inspired by the Smart Dust concept. [153] The **Smart Dust**, that originated even before the start of the Millennium, is a concept of a miniaturized self-contained sensor,

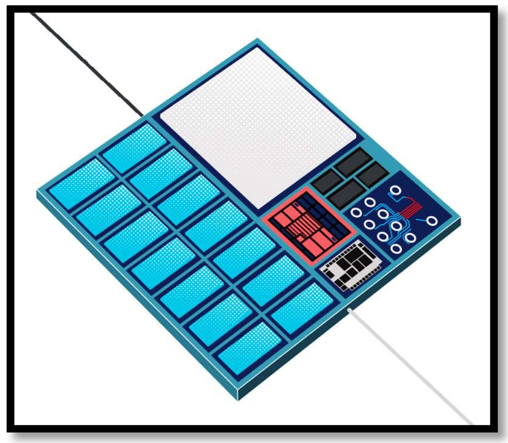

Figure 26: An artist impression of the Integrated Circuit Sprite. The Structure System is a semiconductor substrate on which the remaining Subsystems and Payload are integrated. The Payload, that supports a set of applications, is the dark blue chip that has several white circles. The Power System consists of the Solar Cells on the left half, the Thin Film Battery in the upper corner, and the Power Regulation System, that is placed between payload and battery. The communication system consists of an antenna and radio, respectively the light gray rod, and the gray and black colored chip. The Onboard Data Handling System consists of a microprocessor which is the red and dark blue colored chip. The dark gray rod is an electrodynamic tether that represents the Attitude Determination and Control System as well as the here defined Orbit Control System. [153] [155]

hence the basic subsystems for the IC Sprite. [153] [156] [157] The size of this IC Sprite was inspired by **Space Dust**, which are dust sized objects in space that have unconventional orbital dynamics. [153] They are so small in size and mass that some orbital perturbations due to, for instance, Solar Radiation Pressure, Lorentz Force, and or Atmospheric Drag, cannot be neglected. [158] The three orbital laws of Kepler do therefore not apply and result in an orbit with unconventional orbit dynamics that is often referred to as a **Non-Keplerian Orbit**. Although the IC Sprite was not intended to be as small as Space Dust, it would still be small enough to harvest these Orbital Perturbations so that they could be used for alternative or new space missions. [153] [159] Spacecraft miniaturization comes furthermore along with other advantages, like a decrease in the amount of spacecraft components. Decreasing the amount of components results in an increase of the probability that the spacecraft succeeds to work properly in space. [155] Spacecraft miniaturization comes also along with limitations, like the available power, the amount of instruments, and the amount of data that is stored and transmitted. [153] The idea is to compensate these limitations by increasing the amount of miniaturized spacecraft that are used for the proposed space mission. [153] [155] [159] It is then possible to achieve the same or even more than an equivalent space mission that just makes use of one big spacecraft. In addition, by increasing the amount of spacecraft that are used for a space mission, some room is left for spacecraft that fail or do not work properly in space. The probability of a successful mission is therefore increased as well. [155] Another advantage that comes along is the possibility to use different kind of Distributed Space Systems, which creates new opportunities for space missions. [153] A **Distributed Space System** is defined here as the use of multiple Spacecraft in space as one system. The use of affordable COTS components in combination with a Miniaturized Spacecraft results also in a drastic reduction of the Launch and Spacecraft cost. [160] The launch cost is reduced by decreasing the mass of the spacecraft while the spacecraft cost is lowered because of the use of COTS components. This concept contributes therefore to the current need to reduce the cost of space missions. The significant reduction in cost and the simplification of the spacecraft contributes also to the need to make space missions accessible for everyone. All these advantages resulted in the proposal of different kind of Sprite Spacecraft as well as Mission Concepts that make use of these Sprites. The way each Sprite concept is referred to is not always consistent throughout the literature. For the sake of clarity, each Sprite concept is assigned with a convenient name. [153] [154] [155] [156] [157] [158] [159] [160]

Concepts – Several Sprite Concepts, along with different kind of Mission Concepts, are published since 2007. One of the first Sprite Concepts published in that year is referred to as a Millimeter Scale Lorentz Propelled Spacecraft. [161] As the name already implies, it is a millimeter sized Sprite that is Lorentz Propelled (**LP**). For clarity, this Sprite is referred to as the **LP Sprite**. In 2008 another Sprite Concept is proposed that is known as the Microscale Infinite Impulse (**MII**), which is nothing more than a Microscale Solar Sail [162] [163] For convenience this Sprite is referred to as **MII Sprite**. Both of these Spacecraft have Non-Keplerian Orbits and resulted in the proposal of two types of Formation Flying Mission Concepts. One is referred to as a Constant Radius or Anomaly Formation and the other is called the Along Track Separation Formation. [162] [163] [164] Additional Sprite Concepts are proposed based on the MII Sprite, like a Corner Cube (**CC**) Sprite, for convenience referred to as **CC Sprite**, and a Solar Sail Disk (**SSD**) Sprite, which is for convenience referred to as **SSD Sprite**. The CC Sprite is nothing more than three MII Sprite that form together a corner of a cube. The SSD Sprite is nothing more than a Solar Sail Disk that is sandwiched by two MII Sprite. [162] [163] At the beginning of 2009, an attempt is made to manufacture an Application Specific Integrated Circuit (**ASIC**) Sprite. [165] It seems that since then the aim of the Sprite Project was an ASIC Sprite. [154] An ASIC Sprite is basically the same as the IC Sprite. The only difference is that the ASIC Sprite is used for one specific application while the IC Sprite is used for a set of applications. The attempt to produce an ASIC Sprite back then seems to be too ambitious since shortly thereafter the production of the ASIC Sprite is stopped. [165] The new plan would start first with the design, fabrication and testing of a bigger sized Sprite named Prototype Sprite. They should at least have the same capability as the Sputnik 1 Spacecraft that was launched in 1957. In other words, they would be able to establish a downlink. [165] [166] Once this goal would be achieved, additional Prototype Sprite would be produced that would have the same capability, but are smaller in size and mass. It was expected that in this way, the size and mass would gradually decrease, resulting eventually in the intended ASIC Sprite. [165] The first series of Prototype Sprite that, produced that year, were centimeter sized Printed Circuit Boards (**PCB**) that contained COTS components. They are therefore also known as **PCB Sprite**. One of the PCB Sprite was published in 2010. [167] Another PCB Sprite was published in 2011. [154] [160] The one published in 2011 seems to be made in 2009, while the one published in 2010, seems to be made in 2010. [167] [154] [160] In that same year, an adapted version of the MII Sprite was published that is named Millimeter-Scale Solar Sail (**MSS**). For convenience this Sprite is referred to as **MSS Sprite**. In addition to the earlier mentioned Formation Flying Mission Concepts, other Mission Concepts are proposed that have an orbit in a Fixed Frame. The two proposed fixed frames are referred to as Planet Fixed Frame and Sun-Planet Fixed Frame. Another Mission Concept is suggested where the MSS Sprite is placed in one of the Lagrange Points. [164] There is also a Mission Concept that is proposed in 2010 where an ASIC Sprite is used for an Atmospheric Re-Entry Mission (**ARM**). The ASIC Sprite, referred to as a Microscale Atmospheric Re-Entry Sensor, is named here for convenience **ARM Sprite**. The ARM Sprite has a size and mass that is small enough to survive an atmospheric re-entry and measures the properties of the atmosphere during re-entry. [165] [167] In 2011 another Mission Concept is proposed where an ASIC Sprites is used for an Asteroid Impact Mission (**AIM**). For convenience this Sprite is referred to as the **AIM Sprite**. The idea is to send a cloud of AIM Sprite towards an asteroid. The cloud contains enough AIM Sprite to ensure that after impact with the asteroid a certain amount of AIM Sprite survives. The AIM Sprite that survive determine thereafter the composition of the Asteroid. [154] The last mission that is proposed in 2011 is to launch a crowd funded CubeSat that deploys hundreds of PCB Sprites. [168] [169] The PCB Sprites are packed and stored in spring loaded structures that are placed inside the CubeSat and are kept in place through the spring loaded lid of the CubeSat. (cf. Figure 27). [168] [170] The deployment is initiated on command once the right orbit is achieved. [168] The Sponsors that donate enough get something in return, for example, a PCB Sprite that transmits the initials of the Sponsor once its deployed in space. [171] The crowdfunding is done through Kickstarter which is an initiative launched in 2009 to provide funding for projects that are yet to be realized. [172] The name of this Mission Concept is inspired by the name of this platform and is therefore referred to as KickSat. The sprites used for this concept are therefore for convenience referred to as the **KickSat Sprite**. [154] [160] [161] [162] [163] [164] [165] [166] [167] [168] [169] [170] [171] [172]

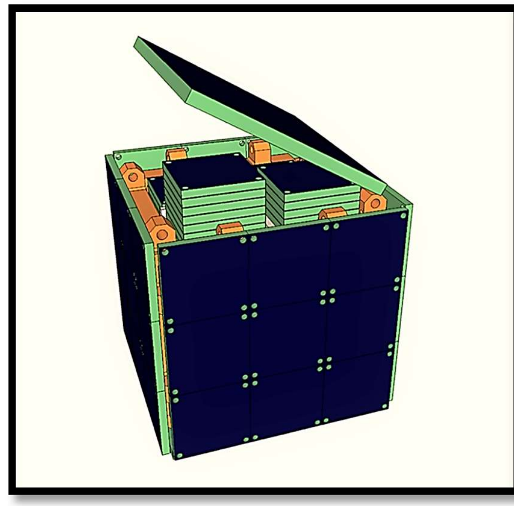

Figure 27: The initial concept of KickSat Project. [170]

Realization – From all these concepts, there were two that were eventually realized. One of them is the PCP Prototype Sprite that was published in 2010. A year later, three of them were launched through the Materials International Space Station Experiment 8 (**MISSE-8**). [173] These PCB Prototype Sprite in particular, are therefore referred to as **M8 Sprite**. In that same year, KickSat managed to get enough sponsors through Kickstarter. Three years later, in 2014, an altered version of KickSat was launched. [152] For convenience, this mission is referred to as **KickSat 1** since another KickSat Mission, here referred to as **KickSat 2**, is expected to be launched in 2017. [152] [173] [174]

8.1 MISSE-8

Intro – In 2010, one of the employees at Cornell University, that worked at that time also on the Sprite Project, got an opportunity to use a spot on the MISSE-8 Pallet. [173] This resulted in the attachment of three PCB Prototype Sprite on one side of the pallet. On the 16th of May in 2011, the MISSE-8 Pallet was launched by the Space Shuttle Endeavor as cargo for the International Space Station (**ISS**). [173] After arrival, the MISSE-8 Pallet would be mounted to the exterior of the ISS and expose its own cargo to the space environment. After three years, the MISSE-8 Palled would be unmounted and return back to Earth with another Space Shuttle. The intention was to start the mission of the M8 Sprite during the exposure. After analysis of the returned samples, the M8 Sprite Mission would end. Although the samples returned, they were faced with an unexpected encounter in space.

Status – The Space Shuttle Endeavor arrived at the ISS as planned. The MISSE-8 Pallet was shortly thereafter successfully mounted on the exterior of the ISS. All the cargo of this pallet, including the M8 Sprite, were exposed to the harsh space environment for more than three years. After the MISSE-8 Pallet was unmounted, it was safely brought back to Earth by the Dragon Spacecraft of SpaceX, on the 18th of March in 2014. Exactly one month earlier, the same Dragon Spacecraft deployed the KickSat 1 spacecraft into orbit after it was launched by the Falcon 9 Launch Vehicle towards the ISS. [174] All three M8 Sprite were returned to Cornell University, where the survivability of the COTS components was assessed. Two of them were still working. Evaluating the survivability was therefore considered to be a success. Unfortunately, it was not possible to determine communication capability of the M8 Sprite. It turned out that the M8 Sprite were fixed on the side of the MISSE-8 Pallet that did not face the Earth. Whether this encounter was unexpected is not clear, although this seems to be the case though. The MISSE-8 Sprite Mission is therefore considered to be a partially successful. [175] [176]

Spacecraft – The three M8 Sprite are stated to be identical. The PCB Prototype Sprite that was published in 2011 is considered to be the initial concept of the MIS8 Sprite. The actual MIS8 Sprite is believed to be the PCB Prototype Sprite that was published in 2010

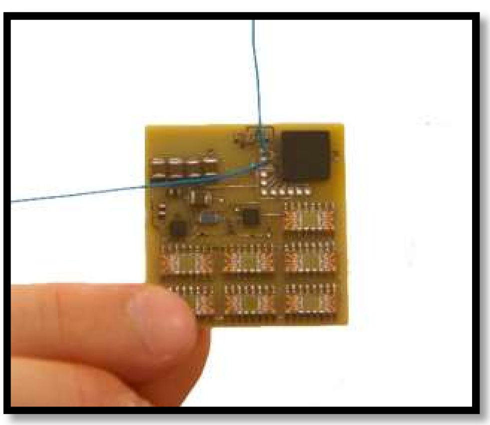

Figure 28: One of the Printed Circuit Board Sprite from 2010. This version might have been used for the M8 Sprite.

(cf. Figure 28) since it looks the same as the photos that were taken of the MIS8 Sprite after they were retrieved. The M8 Sprite has a form of a flat square plate. They were completely build out of COTS components. The main structure, which was the PCB, has a side length of 3,8 cm and a thickness is 1,5 mm [167]. The total mass of the MISSE-8 Sprite was stated to be 8 gram [167]. The identified subsystems are, next to the Structure, the Communication System, Onboard Data Handling System, and Power system. The Onboard Data Handling System was sometimes also considered to be part of the Communication System.

8.2 KICKSAT 1

Intro – On the 18th of April in 2014, KickSat 1 (**KS1**) is launched into space by the Falcon 9 Launch Vehicle as a piggyback on the third Commercial Resupply Service (**CRS-3**) of SpaceX as part of NASAs Educational Launch of NanoSats (**ELaNa**) Program. [152] [177] [178] The KS1 Spacecraft, a CubeSat that exits of 3 CubeSat Unites (**3U CubeSat**), that contains 104 KS1 Sprite, is stored in a so called Poly Picosatellite Orbital Deployer (**P-POD**). [152] The P-POD, which is nothing more than a CubeSat deployer, is placed in the second stage of the Falcon 9 Launch Vehicle together with three more P-PODs that contain in total four other CubeSat. [174] [179] The idea is to deploy the KS1 Spacecraft from the P-POD shortly after the second stage is separated from the Dragon Capsule that carries cargo for the ISS. Right after the deployment, the KS1 Spacecraft is starting to power up and a timer is turned on that prevents the KS1 Sprite to be released on command for another 16 days because of a scheduling conflict with the ISS. Another timer is turned on as well to deploy the antenna of the KS1 Spacecraft after 30 minutes. Forty-five minutes after the deployment of the antenna, the KickSat 1 Spacecraft starts transmitting its Telemetry. Thereafter, it is possible to establish a communication link between the KS1 Spacecraft and Ground Stations on Earth and check the status of the KS1 Spacecraft. The next step is to let the KS1 Spacecraft obtain a stable sun-pointing attitude, which is expected to take about 3 to 4 days. The stable sun-pointing attitude of the KS1 Spacecraft is implemented to make sure that the KS1 Sprite are facing the Sun right after their deployment. The nutation that is experienced by the rotation axis of each of the KS1 Sprite is in this way also minimized. Sixteen days after the deployment of the KS1 Spacecraft, the status and the attitude of the KS1 Spacecraft are checked again. In case everything works as expected, a command is send to the KS1 Spacecraft to initiate the deployment of the KS1 Sprite. The command triggers the burn of a wire on the KS1 Spacecraft. [152] Once the wire is cut, a structure that holds the KS1 sprite in their place is released by a compressed spring and the KS1 spacecraft are deployed (cf. Figure 29). [152 174 180] As is known now, this sequence of events turned out to not go exactly as planned. [152 174 177 178 179 180]

Status – The KS1 Spacecraft is successfully deployed into orbit by the P-POD. [152] The antenna of the KS1 Spacecraft is thereafter also deployed with success resulting in a communication link with the main ground station from Cornell University during its second orbit. [152] Other ground stations around the world that are set up by Radio Amateurs establish thereafter also a communication link with the KS1 Spacecraft and managed to receive its Telemetry. [152] Although not explicitly stated, it is assumed that the desired Sun-Stable Attitude, which takes about three to four days, is also obtained since it is mentioned that the KickSat 1 Spacecraft operated normally until the 30th of April in 2014. [152 174] Thereafter, a power anomaly occurred onboard the KickSat 1 Spacecraft. [152] This resulted in a reset of the electronics of the KS1 Spacecraft, including the timer that prevents the KS1 Sprite to be deployed within 16 days. [152] The cause of this power anomaly is not known, it is believed though that radiation in space is the cause. [174] The new deployment date that is set by timer turns out to be several days after the planned re-entry of the KS1 Spacecraft. [152] Several attempts are made to transmit a command that deploys the KS1 Sprite but without success. [152] The established uplink, through which Telecommands are send, is lost because the uplink radio is not turned on after the reset since the required power to do that is not available. [174] This is presumably due to the previously assumed Sun-Stable Attitude of the KS1 Spacecraft which results in a limited amount of solar cells that are facing the Sun. The remaining orbital time of the KickSat 1 Spacecraft turned out to be not enough to obtain the required power. In the end, the KS 1 Spacecraft, together with the KS1 Sprite onboard, re-entered the atmosphere of the Earth on the 13th of May in 2014. [152] The KickSat 1 mission failed therefore although many other goals are successfully achieved, like realizing a crowd funded space mission. [152 174]

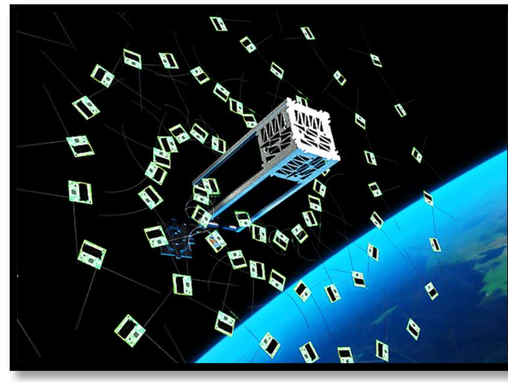

Figure 29: An artist impression of the KickSat 1 Sprite deployment from the KickSat 1 Spacecraft. Note that the renderings of the KickSat Spacecraft and Sprite are not the final designs used for KickSat 1. [180]

Application –The application of the KS1 Mission is not specifically stated. It is assumed that the main idea of the KS1 Mission is to proof that it is possible to establish with the KS1 Sprite downlinks that are distinguishable from one another even though they use the same operating frequency and are in a close vicinity of each other. [152 168 181] The transmitted EMWs of each KS1 Sprite are identified in the same way as the transmitted EMWs of spacecraft that are part of the Global Positioning System (**GPS**), namely through Pseudo Random Noise (**PRN**) that is implemented in the transmissions. [152] **Pseudo Random Noise** is nothing more than a binary sequence that is obtained through a deterministic algorithm and looks like random noise when it is included in transmitted EMWs. The PRN for each KS1 Sprite is unique and is obtained through the deterministic algorithm that is known as the **Gold Codes**. [152] The division of unique codes to multiple communication devices in order to establish simultaneously distinguishable communication links on the same operating frequency is also known as **Code Division Multiple Access** (**CDMA**). [181] Mobile phones make for example also use of CDMA. It simplifies the filtering of EMWs that are received by the receivers since they only need to focus on the received EMWs that have a certain correlation with the code they are looking for, which is in this case the PRN of the KS1 Sprite. This technique is therefore also referred to as **Matched Filtering**. [152] Despite the unique PRN for each KS1 Sprite, there is still a cross correlation between the assigned PRNs that might result in an unacceptable amount of interference between the transmitted EMWs of the KS1 Sprite when they are all in a close vicinity of each other and transmit simultaneously. [152]

Each KS1 Sprite transmits therefore intermittently by turning the sleep mode on and off for a randomized amount of time. [152] This limits the amount of KS1 Sprite that transmit simultaneously and therefore the interference between the transmitted EMWs. In addition, the EMWs that are transmitted by each KS1 Sprite contain also an Error Correction Code (**ECC**) next to the PRN and Telemetry. An **Error Correction Code** is a binary code that is determined by a deterministic algorithm that uses the Telemetry to be transmitted as input and is included in the transmission. It is used by the receiver to check if the received Telemetry is the same as the transmitted Telemetry and correct it to a certain extend in case it is not. The checking and correcting of Telemetry through the ECC is done by the receiver without the use of another transmission of the same Telemetry. It is therefore referred to as **Forward Error Correction**. [152] Once it is proven that it is possible to establish the intended communication links through the aforementioned communication techniques, the idea is to use the KS1 Sprite for other purposes. As a GUS, the KS1 Sprite are, presumably, all equipped with two sensors, namely a magnetometer and a gyroscope. [152] [181] [182] It seems that both COTS sensors are not used in space before and that the KS1 Sprite are used to test these sensors in space first. [182] [183] In case both sensors work in space, they are used for more applications. By combining the measurements of both sensors for each KS1 Sprite it is possible to determine the attitude of each KS1 Sprite. [174] The gyroscope on its own is useful to determine the rotation rate of the KS1 Sprite. This is useful for example for the study of perturbations due to, for instance, the atmosphere. [168] [174] As a Distributed Space System, it is possible to use the magnetometer of each Free Flying KS1 Sprite for Multipoint In Situ Measurements and create a local map of the magnetic field of the Earth. [174] This is something that a bigger sized single spacecraft cannot do in comparison. The sponsors that donated enough money get the opportunity to write part of the software for the KS1 Sprite. It is possible for example to let the KS1 Sprite transmit their own name. One of these sponsors intents to use the RAM in the Microcontroller as a radiation detector. To do that the RAM needs to keep on writing Pseudo-Random Data and read it back repeatedly. In case there are high-energy particles, bits are flipped. Based on the amount of bits flipped, the radiation is estimated. [152] In total, 26 sponsors donated enough money to write their software but in the end only nine of them managed to write their software on time. [152] The KS1 Spacecraft and KS1 Sprite transmit at a frequency that is used by Radio Amateurs. They are therefore encouraged to try receive Telemetry from the KS1 Spacecraft as well as the KS1 Sprite. [181] The KS1 Mission is thus used for several applications. The main application for the KS1 Mission is considered to be proof of concept. As a GUS, the main application is considered to be Technology Demonstration, Multipoint In Situ Measurements, and Orbital Dynamics. Additional applications for the KS1 Mission are for instance Amateur Radio Communication and Education. [152] [168] [174] [181] [182] [183]

Spacecraft

Intro –Three types of Sprites are developed for the KS1 Mission through an iterative design process. They are known as the Souvenir Sprite, Developers Board Sprite, and the Flight Sprite. [174] The Souvenir Sprite is more or less an imitation of the KS1 Sprite. It is send as a souvenir to all the sponsors, so called **Backers**, that donated money to the KS1 Mission through Kickstarter. Each KS1 backer that donated a certain amount of money received in addition a **Developers Board Sprite**. The Developers Board Sprite is a close representation of the KS1 Sprite. It is therefore often mistakenly assumed that this is the KS1 Sprite. It is actually used to provide an opportunity to these backers to write their own software that is later on implemented on one of the KS1 Sprite. In other words, they get the change to have their own personalized KS1 Sprite. The **Flight Sprit** seems to be the Sprite that is actually launched. There is only one photograph available of the, presumably, incomplete Flight Sprite. [174] The closest image that represents the Flight Sprite is actually a rendering (cf. Figure 30). [180]

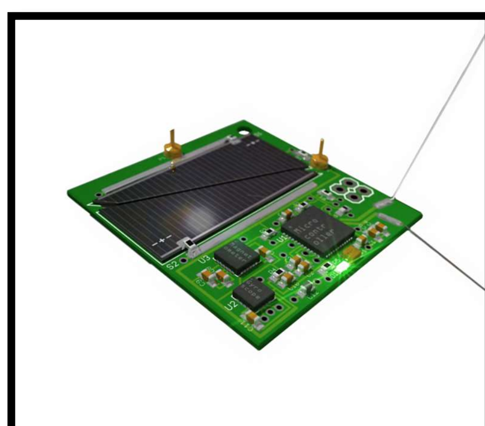

Figure 30: A rendering of what is believed to be the KickSat 1 Sprite. [180]

For convenience this sprite is here already referred to as the **KS1 Sprite**. The mass of the KS1 Sprite is given to be 4 [g]. [152] The KS1 Sprite is completely built out of COTS components. [152] All the components that are used are known since the Bill of Material (BoM) is given. [152] [184] It is not specifically stated though what the payload is and which component is used for each subsystem. The components are therefore assigned to a specific subsystem based on what the component is used for. This resulted in a total of five subsystems for the KS1 Sprite are identified, namely the Structure System, Power System, Communication System, Onboard Data Handling System, and Deployment System. Some of these subsystems are partially integrated with one another. The payload is considered to be represented by one of the subsystems. [152] [174] [180] [184]

9

THE SMALLER BROTHERS OF CUBESAT AND MORE

Intro – KickSat 1 was not the last SOKS Space Mission (**SSM**) that was launched. From 2013 to 2016, more SSMs were launched. For completion, a brief overview is given in chronological time order.

2013 – Four PocketQubes (**PQ**s) (cf. Figure 31) were deployed in orbit through UniSat-5 in 2012. Wren, from Germany, is a 1U PQ. Eagle 2, also known as $50Sat, is a 1,5U PQ from the US. The US had also Eagle 1 and QubeScout-S1, which were both 2,5 PQs. Eagle 1 is, among other, known as T-LogoQube. A PocketQube is the smallest brother of CubeSat. The success of CubeSat came along with an increase of the launch cost. By reducing the spacecraft mass, the increase in launch cost could be compensated. Therefore, the PocketQube was introduces. The PocketQubes, that are each considered to be a SSM, were not the only SOKS that were deployed that year. Another SOKS, known as Pocket PUCP, was also deployed in orbit that year. This SOKS was deployed from PUCP-Sat 1, which is a 1U CubeSat from Peru that was also deployed by UniSat 5 (cf. Figure 32).

Figure 31: The PocketQubes that were deployed by UniSat-5. The spacecraft, what seems to be representative for the flight model, are from left to right Wren, Eagle 2, Eagle 1 and QubeScout 1.

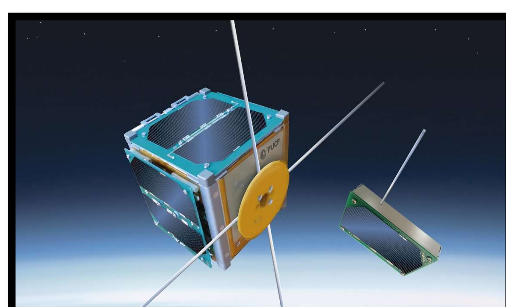

Figure 32: A rendering of Pocket PUCP and PUCP-Sat1

2014 – Next to KickSat 1, there were two more SSMs launched that year. One of them is from the US, namely AeroCube6. This SSM contains two SOKS. They are each a 0.5U CubeSat, which are for convenience referred to as HalfCubes (**HC**). One HQ is named AeroCube 6A or CubeRad A, while the other one is referred to as AeroCube 6B or CubeRad B. They form together a 1U CubeSat in stowed position. After deployment, they are orbiting on their own (cf. Figure 33). The remaining SSMs was from Singapore, and is known as VELOX 1. The 3U CubeSat, named also VELOX 1, deployed the SOKS known as VELOX-P3 (Figure 34). This was the last SSM of that year.

2015 – China seems to have launched their first two Space Missions with SOKS in 2015. Despite the confusion about these missions, it is believed that there were two Spacecraft with each their own two SOKS. The NUDT PhoneSat is believed to contain two chip sized SOKS that were attached to their Antenna (cf. Figure 35). The remaining two SOKS are believed to be part of Naxing 2. It is clear that they were cuboid SOKS, however. They seem to have been actually deployed. In 2015, there seems to be also a SSM from the US that was launched towards the ISS. It was Stanford Nano Picture Satellite that is also known as SNAPS. This SOKS is another smaller brother from the CubeSat that is referred for convenience as QuarterCube (**QC**) since it was a 0.25U CubeSat.

2016 – The last two SSMs are from the US and Brazil. They are both TubeSat. It is also a standardized Spacecraft of which the constrains are defined up front. The TubeSat from the US is referred to as OSNASAT and the one from Brazil as Tancredo-1. They were launched in 2016 towards the ISS and were deployed in orbit in January 2017.

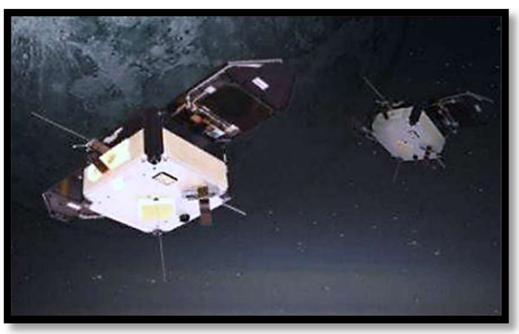

Figure 33: The HalfQubes of AeroCube 6 after deployment.

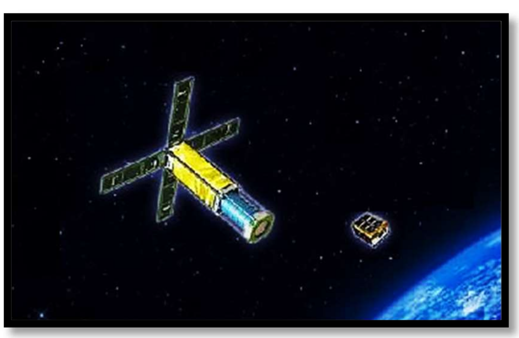

Figure 34: An artist impression of VELOX 1 and VELOX-P3 in orbit

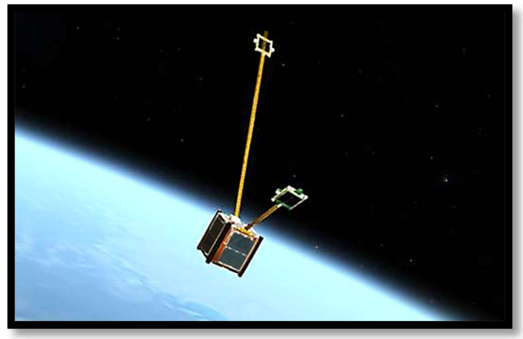

Figure 35: The Sub One Kilogram Spacecraft of the NUDT-PhoneSat after deployment.

– SECTION II –

ANALYSIS AND DISCUSSION OF THE LAUNCHED SPACE MISSIONS

10

THE IDENTIFIED MISSIONS

Intro – The details of the identified Space Missions with Sub One Kilogram Spacecraft (**SOKS**) are provided in Section I. For Chapter 2 to Chapter 8 Extended Literature Study (**ELS**), discussed in Chapter 1.2 is applied. It covers the launched SOKS Space Missions (**SSM**s) between 1957 to 2011, as well as one SSMs from 2014 (KickSat 1). For the remaining SSMs between, that were launched between 2012 to 2016, the ELS is not applied. An overview of these SSMs is given in Chapter 8.

Result – The first SSM was launched already in 1961 and is known as West Ford 1 (**WF1**). The successor of WF1, known as West Ford 2 (**WF2**), was launched in 1963. Pending this launch, a mission related to WF1 and WF2, was launched in 1962, namely West Ford Drag (**WFD**). In that year, additional SSMs were launched. They were all part of the Environmental Research Satellite (**ERS**) program. They are referred to as **ERS1** to **ERS4**. In 1963, only SSMs from the ERS program were launched, namely **ERS5** to **ERS10.** The following year, in 1964, the Dual Calsphere Experiment (**DCE**) was launched. Its successor, the Triple Calsphere Experiment (**TCE**), was launched in 1971. A successor of another SSMs was launched that year as well. This SSM is referred to as Gridsphere Drag Experiment 2 (**GDE2**). Its predecessor, referred to as Gridsphere Drag Experiment 1 (**GDE1**), is launched in 1968. The next SSM that was launched, is in 1992. This SSM is referred to as ODERACS 0 (**OD0**). In 1994 and 1995 its successors are launched. They are known as, respectively, ODERACS 1 (**OD1**) and ODERACS 2 (**OD2**). The following SSMs were launched in 2000. In that year, four SSMs were launched through **OPAL** (Orbiting Picosatellite Automated Launcher). Two of these SSMs were part of the Artemis Project. They are known as Artemis JAK (**JAK**) and Artemis Thelma and Louise (**THEL**). The other two SSMs are respectively known and referred to as StenSat (**STEN**) and the Tethered Aerospace Corporation Spacecraft 1 (**TACS1**). One more SSM was launched in 2000, but this time through MightySat 2.1. It is the successor of TACS1, which is referred to as **TACS2**. The subsequent SSM was launched in 2011 as part of the Materials International Space Station Experiment 8 (**MISSE-8**). This SSM is referred to as the MISSE-8 Sprite (**MIS8**). The successor of MIS8 was launched in 2014 and is known as KickSat 1 (**KS1**). More SSMs were launched between these two launches. They were all launched in 2013 through UniSat 5. One of these SSMs is referred to as PUCP 1 (**PUCP1**). The remaining SSMs, that make use of similar standardizations for their SOKS, are known as Wren (**WREN**), Eagle 1 (**EAG1**), Eagle 2 (**EAG2**) and QubeScout S1 (**SCOUT1**). Additional SSMs were also launched in 2014. One of them is known as AeroCube 6 (**AC6**). The remaining SSM launched in 2014 is referred to as VELOX 1 (**VLOX1**). One of the SSMs that was launched in 2015 is known as the Stanford Nano Picture Satellite (**SNAPS**). Another SSM, that was part of the PhoneSat from the National University of Defense Technology (**NUDT**), is referred to as **NUD**. The remaining SSM of 2015 is known as Naxing 2 (**NAX2**). The SSMs launched in 2016 are known as TanCredo-1 (**TANC1**) and the Open Space Network Satellite OSNASAT (**OSNA**). These SSMs, together with the aforementioned ones, are identified as the SSMs launched between 1957 to 2016.

Discussion – The Mission Name (**MN**) of each SSM in literature was not always conveniently chosen, and or consistently used. In some cases, it was not even defined. To make a clear distinction between the SSMs, some MNs were, where needed, adjusted and or assigned, based on the MNs in literature. The same goes for the abbreviations. In total, 39 SOKS Space Missions that were launched between 1957 to 2016 are identified. At the start of the thesis, it was roughly around 10 SSMs, depending on the reference. The conflicting reference are not a problem anymore for the identified SSMs, thanks to ELS. However, another point of discussion is observed, namely the definition of SSMs. At the start of the thesis it was clear that 1U CubeSat with a mass less than one kilogram would be excluded. In case they would not be excluded, the number of SSMs is expected to grow up to the amount of 1U CubeSat that were launched between 2003 and 2008, which is 33. [185] Next to CubeSat, Tethered Spacecraft that have, in total, a mass more than one kilogram, were also not considered to be a SSM, even though the spacecraft on their own could be considered as SOKS. This was the case with for one MEPSI mission that was launched in 2001 with STS-113. The two MEPSI Spacecraft in this mission had each a mass of about 800 grams. On their own, they could be considered as SOKS. Together, they had a mass more than one kilogram. That is why TACS1 and TACS 2 were each considered as one spacecraft, and not as two separate ones. Another mission that was excluded was MAST, that was launched in 2007. Three Spacecraft were tethered together of which one SOKS. Together, they also had a mass higher than one kilogram. In case this exception would not apply, the 39 SSMs could increase to at least two more SSMs. It could be also reduced to 36 SSMs in case Space Missions with SOKS that are not intended for deployment, or are still attached to the Mother spacecraft after deployment, are excluded, like MIS8, NAX2, and maybe NUD. For NUD it is not known if they were attached to the mother spacecraft, after deployment. It seems likely though since they were not cataloged as orbiting objects.

11

THE MISSION LAUNCH RATES

Results – The obtained information regarding the number of launched SSMs per year resulted in a graphical overview of the Annual Mission Launch Rates for the years between 1957 to 2016 (cf. Figure 36). The **Annual Mission Launch Rate** (**AMLR**) is defined here as the number of launched SSMs in a year that starts at the first of January and ends after the 31st of December. For convenience, the abbreviation LR is used for the AMLR

Analysis – From the 60 years between 1957 to 2016, there were 45 years that had an AMLR of zero, and 15 years that had an AMLR that was higher than that. Seven years thereof had an AMLR of one. From the remaining eight years, there were three years that had an AMLR of five. Two more years had an AMLR of two, and another two years had an AMLR of three. The remaining year had an AMLR of 7. In other words, the largest and lowest amount of years with the same AMLR (45 and 1) had respectively the lowest and highest AMLR (0 and 7). The largest amount of years with the same AMLR above zero (7) was also the lowest AMLR above zero (1). The longest consecutive period of years with the lowest AMLR was between 1972 to 1991. The second largest period with this ALR was between 2001 to 2010. The rest of the years with the minimum AMLR of 0 was not longer than four consecutive years. The longest consecutive period of years with an AMLR above the minimum was four years. One was between 1961 to 1964 and the other one was between 2013 to 2016. For the first period, from 1961 to 1964, the AMLR increased for two years in a row, and decreases then for a year. For the second period, from 2013 to 2016, the AMLR decreased for a year, remained thereafter the same for a year, and decreased then again for a year.

Discussion – The overview of the Annual Mission Launch Rate (cf. Figure 36) can somehow be misleading without the knowledge that is provided in Section I. From the literature study of Project West Ford, discussed in Chapter 2, it is clear that the first launch of the SSM in 1961 (WF1) did not result in the increase of the AMLR in the two years thereafter. Its controversy did limit to a certain extend the AMLR after 1963. The main reason, however, was caused by the success booked by Syncom in 1963. This Spacecraft, that was back then categorized as Active Spacecraft, was the opposite of WF1, which was categorized as Passive Spacecraft. As was discussed in Chapter 1, both type of spacecraft were in a battle with each other to become the next big thing in space. The outcome is clear. Active Spacecraft were proven to be capable of doing more than Passive Spacecraft. The smallest Active Spacecraft at that time was the Tetrahedral Research Satellite (**TRS**) Mark I (c.f. Chapter 3) gave the AMLR of SSMs a boost for two years. This did not last long though since Active Spacecraft were also proven to be able to do more, with more. The TRS families that followed show this clearly (cf. Figure 8, Chapter 2). These two developments, as well as the available technology at that time, which more or less limited Sub One Kilogram Spacecraft to the back then called Passive Spacecraft, resulted in the limited AMLR from 1964 on, until 2000. The year 1963 is therefore considered to be a turning point for SSMs. Based on the ANML only, it might look as if the SSMs were successful at the beginning of the Space Age, which was thus, not the case. Even for the periods with an AMLR, Section I is of importance. The Annual Launch Rate shows clearly two periods of time where SSMs were not launched. The first period is between 1972 to 1991, and the

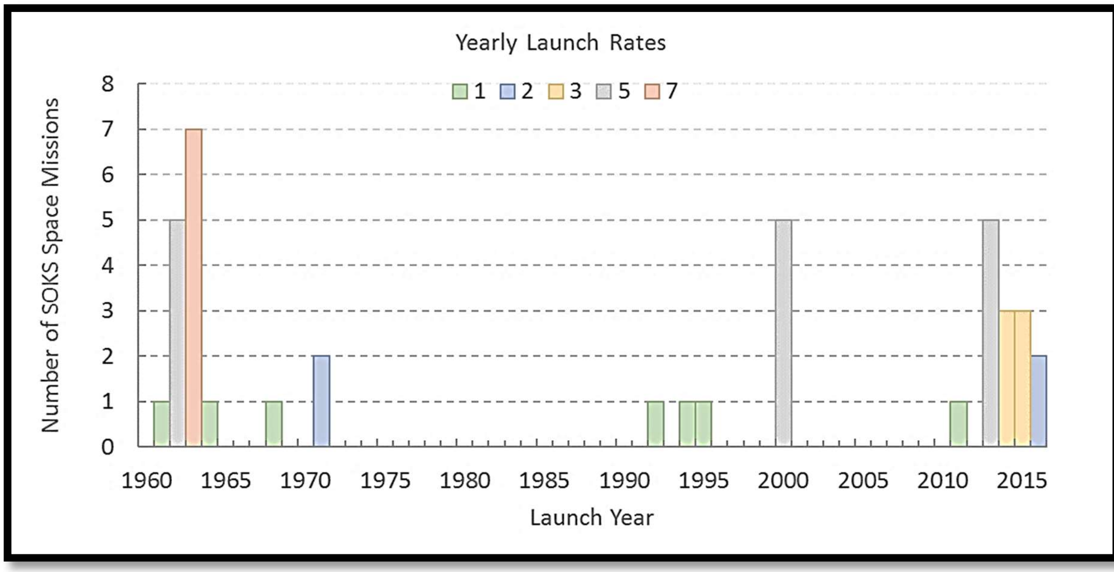

Figure 36: The Annual Launch Rates of Space Missions with Sub One Kilogram Spacecraft.The omitted years, 1957 to 1959, have each an Annual Launch Rate of zero. Abbreviations: ALR, Annual Launch Rate; SOKS, Sub One Kilogram Spacecraft; SSM, SOKS Space Mission.

second period is between 2001 to 2010. The second period could have had more years with an AMLR higher than 0, if 1U CubeSat were not excluded. In case they are included, it is expected that there are going to be additional AMLRs in the years 2003, 2005, 2006, 2007 and 2008, up to respectively 5, 3, 16, 6 and 3. Based on the AMLR in 2000, and the decade thereafter, it might be interpreted as if OPAL failed to make SSMs a success. However, the literature study of OPAL, discussed in Chapter 7, provides the knowledge that the CubeSat is a successor of the SSMs that were launched OPAL. In other words, the SSMs launched in 2000 resulted in the CubeSat. The success of the CubeSat resulted again in the AMLRs after 2010. The goal of the OPAL mission to trigger the launch of SSMs was in the end still achieved, but only a decade later. Based on this knowledge, the year 2000 is considered to be a turning point for SSMs. In case only the AMLR is considered, it might look as if OPAL did not result into anything, even though that is not the case. Other misinterpretations could be that the first consecutive years with an AMLR higher than 0, were more successful than the most recent consecutive years. The decrease in AMLR in the past four years might also be interpreted as if SSMs are not going to be the next big thing. Without Section I, it is already clear that the four-year period is too short to justify a conclusions based on that. With the knowledge that more SSMs were planned for 2016, like KickSat 2 and three more PocketQubes through UniSat-7, this view might change as well. It is expected that these SSMs are going to be launched in 2017. If so, they AMLR would already be higher than that of 2016. However, these argumentations are also not enough to state that the opposite is true.

12

THE MISSIONS CATEGORIZED BY COUNTRY

Results – The SSMs that were launched before 2013 were all from the United States (**US**). Occasionally, other countries were, to a certain extent, involved as well. For instance, the Triple Calsphere Experiment was done in collaboration with the United Kingdom. Another example were the Needles of OD2. They were also used by Russia (**RU**) to test the detection capability of their ground stations. There were also SSMs from other countries after 2012. In 2013, there were two SSMs that were each from another country. One of them, WREN, was from Germany (**DE**) and the other one, PUCP1, was from Peru (**PE**). In the following year, 2014, a SSMs was launched that was from Singapore (**SG**), namely VLOX1. The SSMs NUPS and NAX2, launched in 2015, were from China (**CN**). In 2016, there was one SSM that was from Brazil (**BR**), namely TANC1. The remaining SSMs, that were launched between 2013 to 2016, were all from the US. Based on this information, it was possible to categorize the launched SSMs by Country (cf. Figure 37).

Analysis –The first country with a SSM was from the US. The 26 SSMs that were launched between 1957 to 2012, were all from the US too (cf. Figure 37). In addition, the US had seven more SSMs between 2013 to 2016. During that period, SSMs of five more countries were launched. Germany and Peru were the first to join with their own SSM, other than the US, in 2013. A year later, in 2014, Singapore joined with its own SSM. China followed thereafter in 2015 with two SSMs of their own. In 2016, one more country joined with its own SSM, namely Brazil. There were in total six countries with either one or more SSMs, of which five of them had their first SSM launched between 2013 to 2016. In other words, 85 [%] of all the SSMs, between 1957 to 2016, were from the US. About 5 [%] of these SSMs were from China. The remaining 10 [%] of the SSMs were shared equally by the other 4 countries (DE, PE, SG, and BR). This comes down to 2,5 [%] of the SSMs for each of these countries.

Discussion – The categorization by country of the AMLRs of SSMs shows clearly some new insights. This is especially the case for the period between 2013 to 2016. Since 2013, four more countries had their own SSM, and one more country had two SSMs launched. The sudden increase of countries with their own SSMs, suggests strongly that SSMs are gaining in popularity. Especially since there were no other countries with SSMs before 2012. This information gives a new insight on whether SSMs are expected to be the next big thing. Based on the countries, there seems to be an interest in SSMs on global scale. They are from different continents, namely South America, North America, Europe, and Asia. In case Europe and Asia are considered as one continent (Eurasia), then it is of course three, but that does not change the observation. For the year 2017, at least two more countries are scheduled to join the list of countries with their own SSMs through the launch of UniSat-7, namely Hungary (**HU**) and Argentina (**AR**). The fact that not only the wealthiest countries are able to launch their own SSMs suggest that the SSMs are affordable and that the potential market SSMs is expandable to any country in the world.

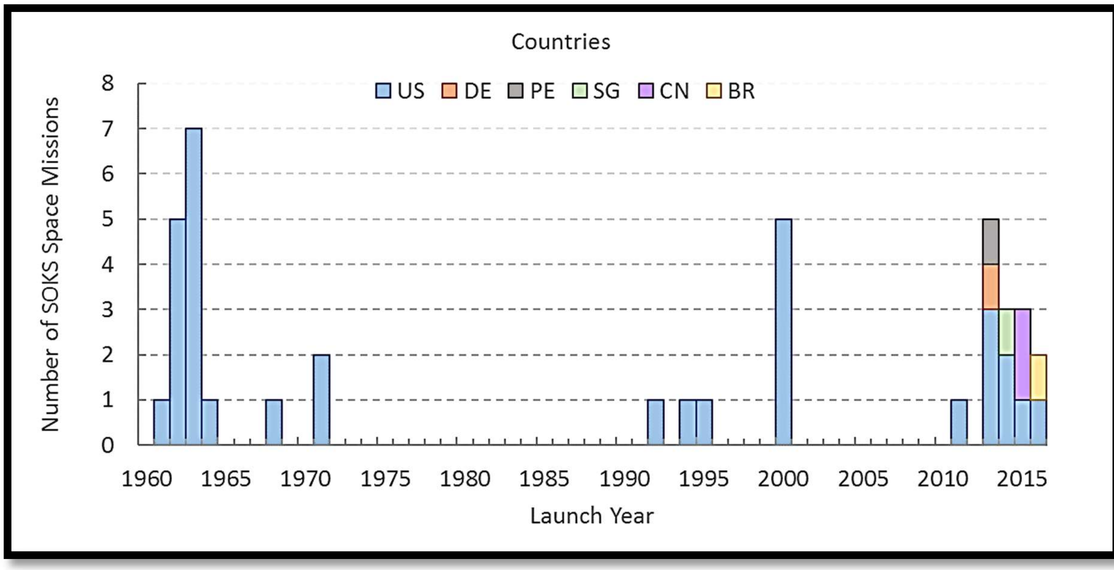

Figure 37: The Annual Launches of Space Missions with Sub One Kilogram by Country. Abbreviations: SOKS, Sub One Kilogram Spacecraft.

13

THE MISSIONS CATEGORIZED BY SPACECRAFT

Intro – Different type of Sub One Kilogram Spacecraft were used for the SOKS Space Missions. Despite the differences, there were also some similarities between them. During the Extended Literature Study, the number of subsystems for each of the SOKS, as well as the SOKS geometry, was determined. The relation between the SOKS, either through the Mission their part of, or the SOKS standards that were used, was determined as well. Based on these SOKS categories, it was possible to categorize the SSMs in three more ways, namely by the number of SOKS Subsystems, the SOKS Geometry (cf. Figure 39), and the SOKs Family (Figure 40).

13.1 SUBSYSTEMS

Results – The West Ford Needles, Calspheres, Mylar Balloons, and the ODERACS Spacecraft did not have any subsystem. The remaining SOKS contained each at least the following four subsystems, namely a Structure System, Power System, Communication System, and Onboard Data Handling System. Occasionally, either a Thermal Control System (TRS Mark I), or an Attitude Control System (StenSat) was included, put they were always Passive Control Systems. None of the SOKS had an Orbit Control System. One of the SOKS (KickSat 1 Sprite) introduced a subsystem that is usually not considered, namely a Deployment System. In other words, there were SOKS with no features, and SOKS with some features, but none of them contained the same features as a bigger sized spacecraft. The SOKS with no subsystems are for convenience defined as **Unfeatured SOKS** (**UFS**). The SOKS with some of the typical subsystems of bigger sized Spacecraft are referred to as **Featured SOKS** (**FS**). **Smart SOKS** would in that case be a defined as SOKS with at least all of the typical subsystems of bigger sized Spacecraft. The categorized SSMs, based on the SOKS Subsystems, are graphically represented (cf. Figure 38) for the analysis and discussion thereof.

Analysis – It is clear that from 2000 on, only SSMs were launched with Featured SOKs (cf. Figure 38). Before the start of the Millennium, with an exception at the start of the Space Age, only SSMs were launched unfeatured SOKS.

Discussion – The aforementioned exception is the TRS Mark I (Chapter 2). This was back then the smallest Spacecraft with subsystems. At the start of the Space Age, it was yet to be decided which Spacecraft would be more superior, Spacecraft with subsystems, or without. They were known as Active Spacecraft and Passive Spacecraft respectively. This explains the Featured SOKS at the start of the Space Age. They were not launched in the years thereafter since bigger sized spacecraft were proven to be able to do more, with more. This development contributed to the decades where a limited amount of SSMs were launched with only Unfeatured SOKS. However, the Technology Advancement seems to have played a more important role. This is visualized by the Featured

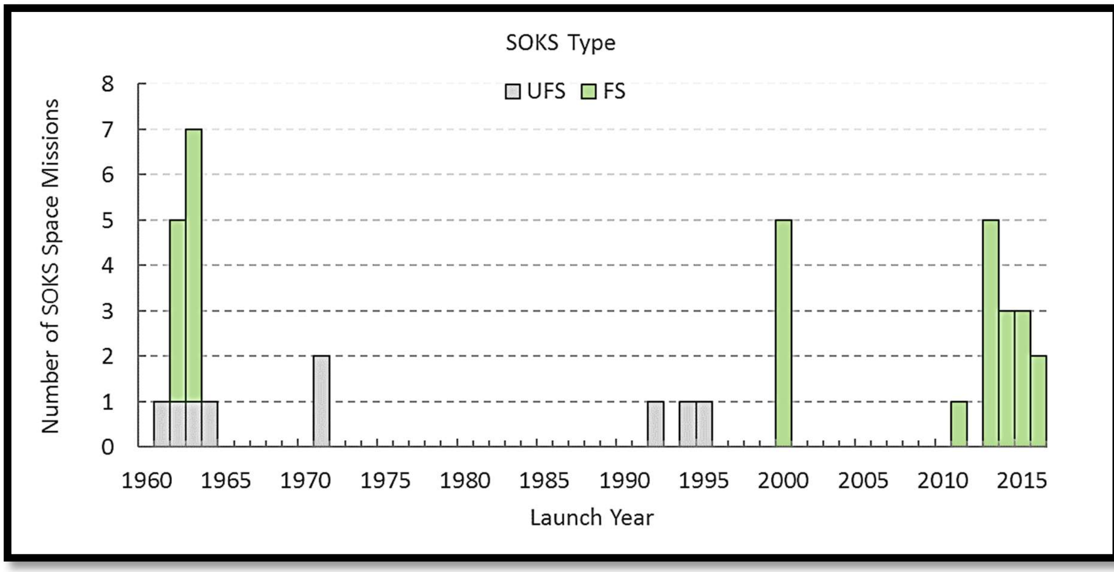

Figure 38: The Space Missions with Unfeatured and Featured Sub One Kilogram Spacecraft.UFS stands for Unfeatured Sub One Kilogram Spacecraft (SOKS), which are SOKS that have no subsystems. FS are Featured SOKS and are defined as SOKS that contain some typical subsystems of bigger sized spacecraft. SOKS with at least all the typical subsystems are defined as Smart SOKS. So far, no SMART SOKS have been launched.

and Unfeatured SOKS that were used for the SSMs before, and after 2000. The advancements of miniaturized electronics could therefore play an important role whether SOKS could be the next thing, or the next big thing within the Space Industry. The technology advancements are apparently also not enough advanced since there has not been a SSMs so far that launched Smart SOKS.

13.2 GEOMETRIES

Results – The West Ford and ODERACS 2 Needles are considered to be a thin (flexible) cylinders. The TubeSats are considered to be a cylinder. The TRS Mark I are each a Tetrahedron. The Calspheres, Mylar Balloons, and ODERACs Spheres have a Spherical Geometry. The KickSat-1 Sprite, together with the SOKS of Naxing 2, categorized as flat cuboid. Wren is the only one that is a cube. The remaining SOKS are all considered to be cuboids. The categorized SSMs, based on the SOKS Geometry, are graphically represented (cf. Figure 39) for the analysis and discussion thereof.

Analysis – The launched SSMs used varying SOKS Geometries over time (cf. Figure 39). Three types of SOKS geometries were used for the SSMs in the first half of the 1960s, namely thin (flexible) cylinders, tetrahedrons, and spheres. Thereafter, until the start of 2000, only spherical SOKS were used for the SSMs. An exception is the SSM of 1995, where a combination of spherical and thin cylindrical SOKS were used. From the start of the Millennium, the SOKS geometries of the SSMs were either cuboids, flat cuboids, cubes, or cylinders. Most of the SSMs had SOKs that were a cuboid.

Discussion – In total seven SOKS Geometries are identified, but this number depends on the geometry types that are considered. It could be less if, for instance, a cube is considered to be a cuboid. The same applies for a flat cuboid, which is actually a chip sized SOKS in this case. It could also be more in case a distinction is made between a thin cylinder that is solid, and a thin flexible cylinder, which is in this case a thin wire. Although the Cuboid is the most used geometry for the SSMs that were launched in the past, it is clear that it is not the standard for the SSMs launched after 2010 (cf. Figure 39). From the 14 SSMs that were launched in that period, eight of them used a cuboid and one of them used a cube. The other SSMs made used of either a flat cuboid, or cylindrical SOKS. Although the number of SSMs is not enough to conclude something concrete, it does provide some new information. There does not seem to be a clear

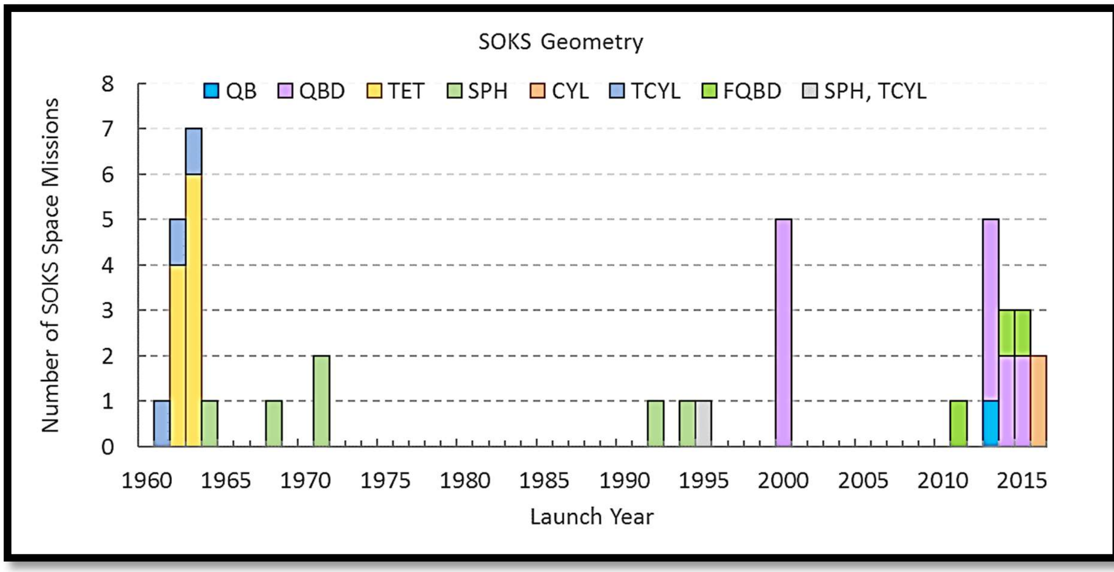

Figure 39: The geometry of the Sub One Kilogram Spacecraft for each Space Mission. Abbreviations: SOKS, Sub One Kilogram Spacecraft; QB, Cube; QBD, Cuboid; TET, Tetrahedron; SPH, Sphere; CYL, Cylinder; TCYL, (Flexible) Thin Cylinder; FQBD, Flat Cuboid.

standard yet for SOKS, as was the case for as was the case for CubeSat, right after its introduction. Another observation is that only one SSM made use of two geometries, namely ODERACs 2. This choice was required to make the mission a success (Chapter 6). Another observation is that the three geometry types that were used for the SSMs before 2000, were not used anymore thereafter (cf. Figure 39). This seems to be also due to the same reason. Based on Section I, it is clear that all the SSMs based their SOKS Geometry on their application, while after 1999, it was the other way around. The SOKs Geometry was fixed, and the application of the SSMs were based on the fixed geometry. In that respect, the year 200 could again be marked as a turning point, but this time for the design approach of the SOKS. It seems that, before 2000, a Top Down Approach was applied for the SOKS Geometry. Thereafter, it seems that a Bottom Down Approach was applied.

13.3 FAMILIES

Results – Several SOKS Families are identified based the SOKS of the SSMs discussed in Chapter 2 to Chapter 9. The identified SOKS Family based on Chapter 2 to Chapter 8 are respectively referred to as West Ford, Tetrahedral Research Satellite, Calsphere, Mylar Balloon, ODERACS, OPAL, and Sprite. Based on the SOKS of Chapter 9, four more SOKS families are identified, and referred to as PocketQube, HalfCube, QuarterCube and TubeSat. The SOKS that are not considered to have their own family are the Pocket PUCP, VLOX-P3, the SOKS of NUDT, and the SOKS of NAX2 since their SOKs are not related to SOKS of other SSMs. Based on the identified SOKS Families, it was possible to categorize the SSMs. A graphical representation is used (cf. Figure 40) for the analysis and discussion.

Analysis –During the 1960s, the SSMs used four of the identified SOKS Families (cf. Figure 40). Around the Millennium, there were SSMs that used SOKS from two more families. From 2010 and on, SSMs used five of the SOKS Families. During that period, SOKS were also used by SSMs that were not part of a SOKS Family.

Discussion – It is clear that the SSMs did not use one SOKS Family in particular, but that it varied in time (cf. Figure 40). Between 1960, up to 2000, there were 25 SSMs launched that used six different SOKS families. From 2011 up to 2016, the same number of SOKS Families is observed, but this time, they are divided over 14 SSMs. In case the SOKS of the Miscellaneous SOKS Family would be considered as SOKS Families

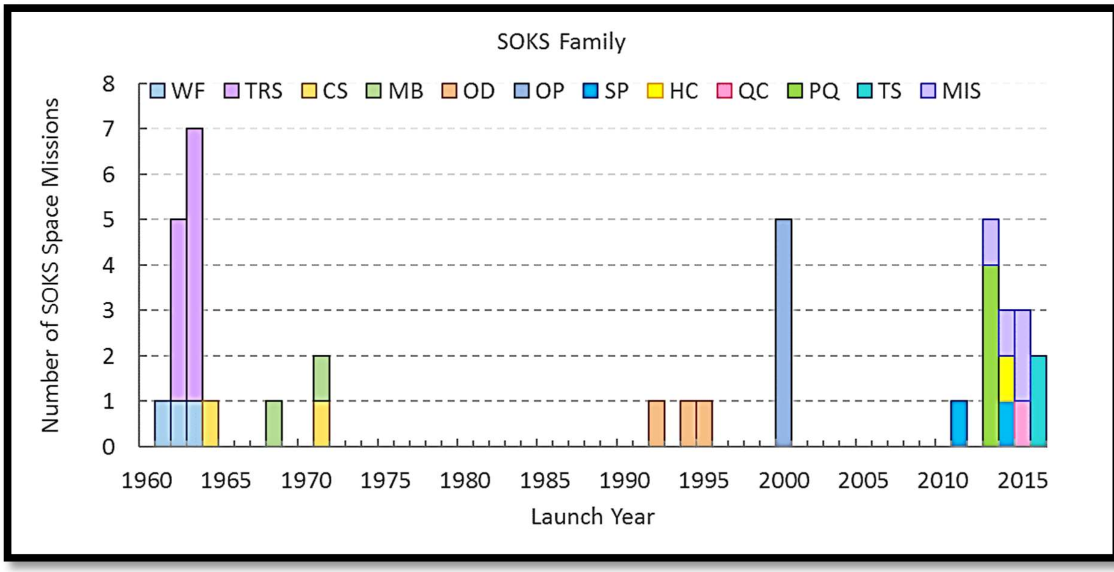

Figure 40: The family of the Sub One Kilogram Spacecraft, for each Space Mission. Abbreviations: SOKS, Sub One Kilogram Spacecraft; WF, West Ford; TRS, Tetrahedral Research Satellite Mark I; CS, Calsphere; MB, Mylar Balloon; OD, ODERACS; OP, OPAL; SP, Sprite; HC, HalfCube, QC, QuarterCube; PQ, PocketQube; TS, TubeSat; MIS, Miscellaneous.

on their own, the total amount of SOKS families would be 9. The categorized SSMs by SOKS Geometry showed already some variety between the SOKS (cf. Figure 39). The categorization by SOKS Family confirms this variation even more. The identified SOKS Families for that period show already that there are several SOKS Standards. However, the graphical representation shows that none of the SOKS Standards is widely applied yet. The variety in standards, as well as the variety in launched SOKS for the SSMs in a relatively short period of time, imply that the market for SSMs is just in its infancy. Taking the miscellaneous SOKS into account, it seems that the possibilities of SSMs are yet to be discovered as well.

– SECTION III –

CONCLUSIONS AND RECOMMENDATIONS

14

CONCLUSIONS

14.1 FIRST RESEARCH QUESTION

Recapitulation – What are all the space missions, in the literature within disposal, that can be categorized, despite conflicting literature, as 'Space Missions with Sub One Kilogram Spacecraft that were launched in the past between 1957 to 2016', after, first defining and then, applying a systematic literature study that can overcome the conflicting literature issue.

Conclusions – The defined systematic approach to overcome the issue with conflicting literature is named Extended Literature Study (**ELS**). The details of ELS are briefly discussed in the Methodology paragraph of Chapter 1.2. The literature study was, as the name already implies, very extensive. The intensity of the ELS was not for nothing. The result is, without a doubt, one of the most complete overview so far of Space Missions with Sub One Kilogram Spacecraft that were launched between 1957 to 2016 (cf. Table 2).

14.2 SECOND RESEARCH QUESTION

Recapitulation – What are the details of the mission characteristics, in particular that of the, launch date, country, status, and application, for each of the identified Space Missions with Sub One Kilogram Spacecraft, that were obtained through the applied literature study.

Conclusions – The details of the mission characteristics that were obtained through ELS are discussed in Section I from Chapter 2 to Chapter 8.

Table 2: An overview of the identified Space Missions with Sub One Kilogram Spacecraft. Abbreviations: LY, Launch Year; LR, Launch Rate; LD, Launch Date; MN, Mission Name; NA, Nation; TYP, Type; GEO, SOKS Geometry; FAM; SOKS Family; SOKS, Sub One Kilogram Spacecraft.

LY	LR	LD	MN	NA	TYP	GEO	FAM
1961	1	21-Oct	WF1	US	UFS	TCYL	WF
1962	5	09-Apr	WFD	US	UFS	TCYL	WF
		17-Sep	ERS2	US	FS	TET	TRS
		11-Nov	ERS1	US	FS	TET	TRS
		17-Dec	ERS3	US	FS	TET	TRS
			ERS4	US	FS	TET	TRS
1963	7	09-May	WF2	US	UFS	TCYL	WF
			ERS5	US	FS	TET	TRS
			ERS6	US	FS	TET	TRS
		12-Jun	ERS7	US	FS	TET	TRS
			ERS8	US	FS	TET	TRS
		19-Jul	ERS9	US	FS	TET	TRS
			ERS10	US	FS	TET	TRS
1964	1	06-Oct	DCE	US	UFS	SPH	CS
1968	1	16-Aug	GDE1	US	US	SPH	MB
1971	2	17-Feb	TCE	US	UFS	SPH	CS
		07-Aug	GDE2	US	UFS	SPH	MB
1992	1	02-Dec	OD0	US	UFS	SPH	OD
1994	1	03-Feb	OD1	US	UFS	SPH	OD
1995	1	03-Feb	OD2	US	UFS	SP+TC	OD
2000	5	27-Jan	TACS1	US	FS	QBD	OP
			STEN	US	FS	QBD	OP
			JAK	US	FS	QBD	OP
			THEL	US	FS	QBD	OP
		19-Jul	TACS2	US	FS	QBD	OP
2011	1	16-May	MIS8	US	FS	FQBD	SP
2013	5	21-Nov	WREN	DE	FS	QB	PQ
			EAG1	US	FS	QBD	PQ
			EAG2	US	FS	QBD	PQ
			SCOUT1	US	FS	QBD	PQ
			PUCP1	PE	FS	QBD	MIS
2014	3	18-Apr	KS1	US	FS	FQBD	SP
		19-Jun	AC6	US	FS	QBD	HC
		30-Jun	VLOX1	SG	FS	QBD	MIS
2015	3	09-May	NUD	CN	FS	FQBD	MIS
			NAX2	CN	FS	QBD	MIS
		06-Dec	SNAPS	US	FS	QBD	QC
2016	2	9-Dec	TANC1	BR	FS	CYL	TS
			OSNA	US	FS	CYL	TS

Each of these paragraphs is a summary of the all the information that was obtained regarding the discussed mission characteristic. Many insights were only possible through the collection and combination of all the related literature that was within reach. This time intensive process resulted in a dense and complete discussion of the mission characteristics. However, due to its intensity, ELS is only applied to the SOKS Space Missions (**SSM**s) that were obtained after 2014. Instead, an overview is given in Chapter 9 of these SSMs. The information combined resulted in a complete overview of the mission characteristics for the SSMs between 1957 to 2011, and a limited overview thereof for the SSMs between 2012 to 2016 (cf. Table 2).

14.3 THIRD RESEARCH QUESTION

Recapitulation – Does a graphical overview of the obtained mission characteristics, over the period between 1957 to 2016, provide an observable trend or insight that can be used to address the research statement?

Conclusion – The annual launch rates, provide in particular the information that SSMs were not common to launch in the past. Based on this graphical overview only (cf. Figure 36, Chapter 11), it can be seen that the launch rates were decreasing in the last four years, which might suggest the opposite of the research statement. The Graphical overview of the countries (cf. Figure 37, Chapter 12) on the other hand shows that since 2012, five more countries launched their own SSMs. Before that, only the US launched them. The analysis of the number of subsystems of the SOKS resulted in the identification of three types of SOKS, namely Unfeatured SOKS, Featured SOKS and SMART SOKS (Chapter 13). Categorizing the SSMs based on these types of SOKS (cf. Figure 38) provided the insight of a clear division between two eras, the Unfeatured SOKS Era and the Featured SOKS Era. The technology advancements during the 1990s played an important part for the turning point. Smart SOKS are however not launched yet, which could mean that the Technology is not advanced enough to let SSMs be the next big thing. From the categorization of SSMs by the SOKS Geometry, some variation in geometries was observed (Chapter 13.2). The identification of the Families and the categorization of the SSMs (cf. Figure 40, Chapter 13.3) provided better insights. One of them was that the market for SSMs is just in its infancy.

14.4 RESEARCH STATEMENT

Recapitulation – The Space Missions with Sub One Kilogram Spacecraft that were launched in the past might rule out whether the next big thing in space would be Sub One Kilogram Spacecraft.

Conclusion – Based on the literature study, combined with the answers to the research questions, it was possible to address the research statement. Throughout the history of SSMs, there are two main turning points identified, as well as two eras for SSMs (cf. Figure 41). The first one is at the beginning of the space age, namely in 1963. The success of the back than called active Spacecraft outshined the so called passive spacecraft which was also not in favor due to the controversy around West Ford Drag. For more than three decades, only unfeatured SOKS were used, in particular, as target objects. The advancements of electronics at the end of the 1990s, resulted in the next turning point, namely in 2000. For the first time since 1964, again featured SOKS were used. It turned out to be a big success that is nowadays known as CubeSat. This explains the period of 10 years thereafter without launch. The success of CubeSat resulted in the end also in the launch of SSMs at the start of this decade. Thus, although it looks like the launch of 2000 failed to start a new era, on the long term, it can be concluded that it did not. Since 2012 several countries launched their SSMs, which is also something remarkable. Especially taking into account that the US was the only country with SSMs, before 2012. The decrease in annual launch rate can therefore imply the wrong impression (Chapter 11). The launches of SSMs is just at the beginning of its journey (Chapter 13.3). Which way it will end is not yet sure. The difference with CubeSat is that, now, there are more than just one standardized spacecraft. Based on the spacecraft that are going to be the standard in the future, two outcomes could be concluded for the statement. Based on the country trend and the different types of standards used and launched, it is concluded that SSMs are just at their infancy. Space Missions with SOKS are, thus, going to be the next thing. Whether it is going to be the next Big Thing, depends on the SOKS that are going to be the standard. Some of the current SOKS are more focusing on keeping the budgets within reach of universities, like PocketQubes. It is an answer to the success of the CubeSat, that came along with an increase in launch cost. The other type of SOKS might impact on a bigger scale since cost can be shared and the target audience can grow to basically to everyone.

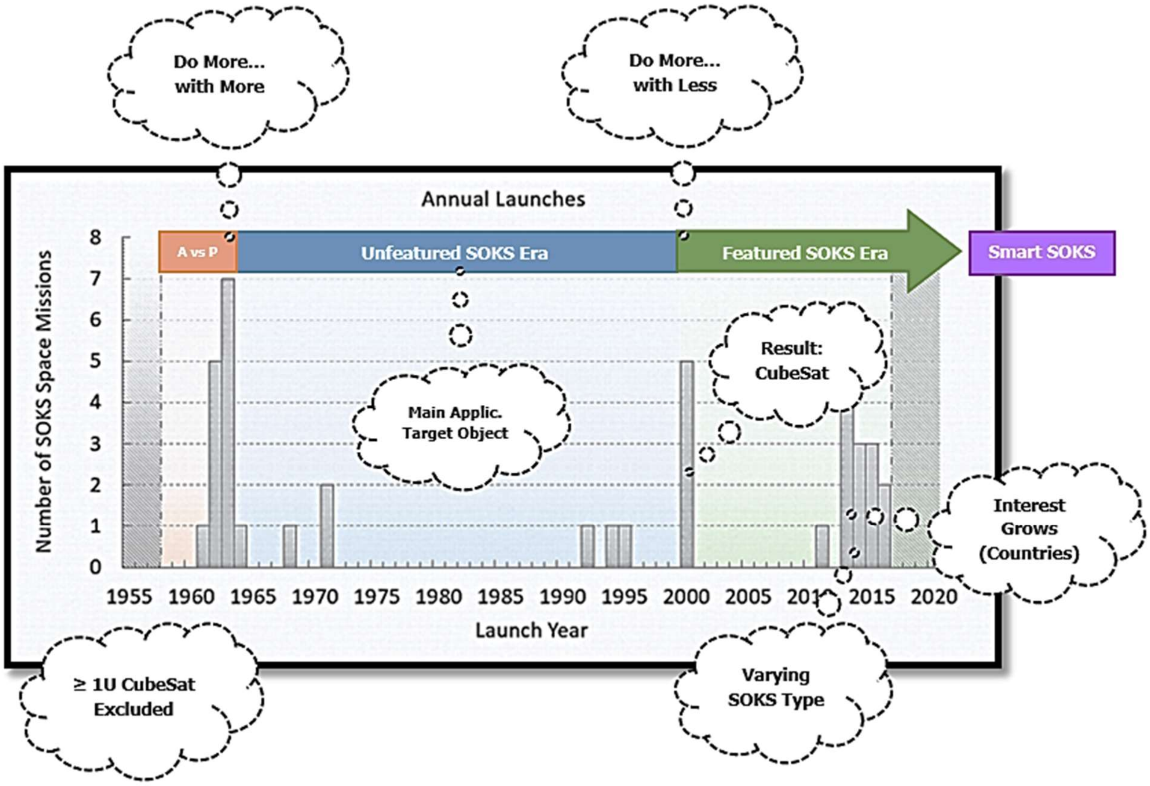

Figure 41: Graphical overview of the conclusions, based on the analyzed and discussed results.

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