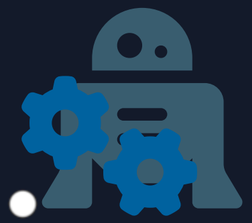

Houston, We Have a Problem

Analyzing the Security of Low Earth Orbit Satellites

Johannes Willbold


@jwillbold


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$whoami

RUHR UNIVERSITÄT BOCHUM RUB

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- Subgroup Chair @ IEEE SA Space System Cybersecurity Working Group
- Hack-a-Sat 2 & 4 Finals

Space Odyssey

Space Odyssey: An Experimental Software Security Analysis of Satellites

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Distinguished Paper Award

***Abstract*—Satellites are an essential aspect of our modern society and have contributed significantly to the way we live today, most notable through modern telecommunications, global positioning, and Earth observation. In recent years, and especially in the wake of the *New Space Era*, the number of satellite deployments has seen explosive growth. Despite its critical importance, little academic research has been conducted on satellite security and, in particular, on the security of onboard firmware. This lack likely stems from by now outdated assumptions on achieving security by obscurity, effectively preventing meaningful research on satellite firmware.**

In this paper, we first provide a taxonomy of threats

in 2022 [2]. The vast majority of these satellites form mega-constellations like *Starlink*, which plans to launch more than 40,000 satellites in the coming years [3].

Small satellites [4] are at the heart of this *New Space Era* as their size and the widespread use of Commercial off-the-shelf (COTS) components makes them affordable even for small institutions. Furthermore, they cover a broad spectrum of use cases ranging from commercial applications (like Earth observation, machine-to-machine communication, and Internet services) to research applications, such as technology testing, weather and earthquake forecasting, and even interplanetary missions [5]–[8].

44th IEEE Symposium on Security and Privacy (S&P)

Applications

Telecommunications

Global Positioning

Earth Obervation

Research

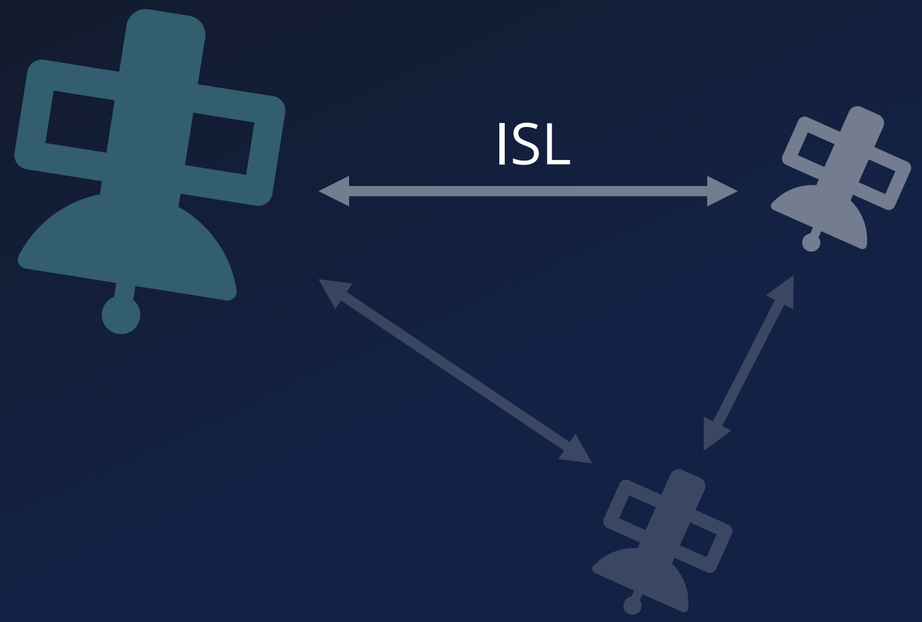
Technology Testing

Context

Space Segment

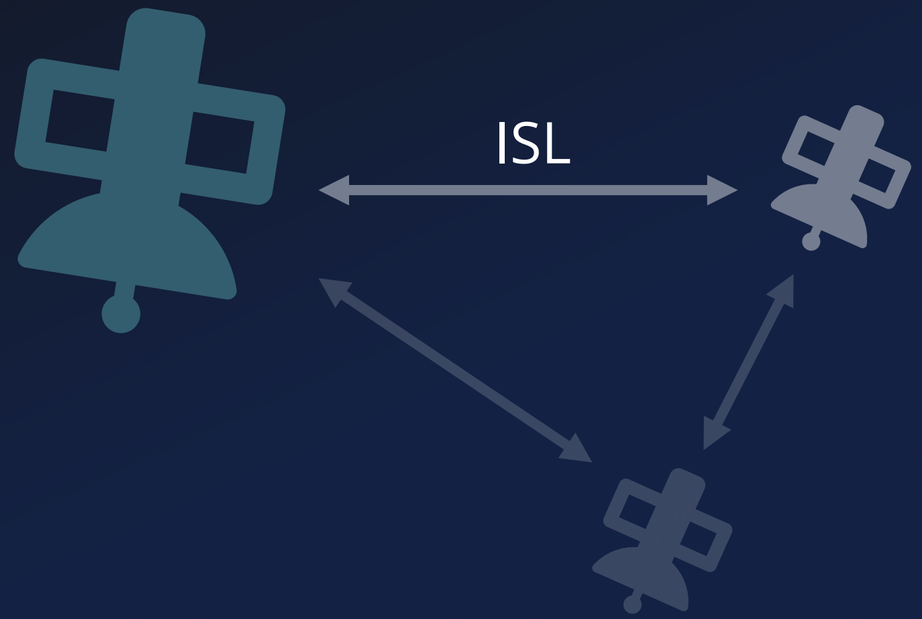
Context

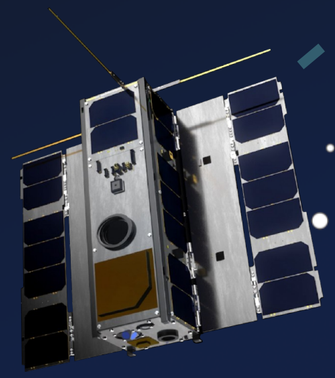
Space Segment



Context

Space Segment



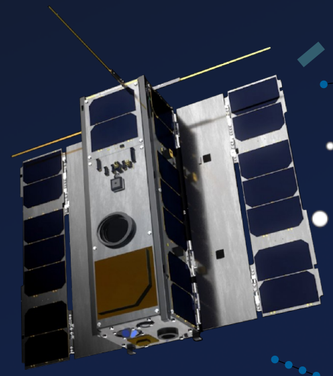


3U CubeSat

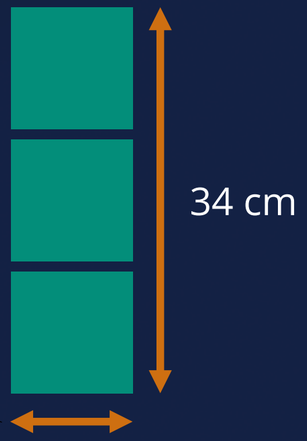
Context

Space Segment

ISL

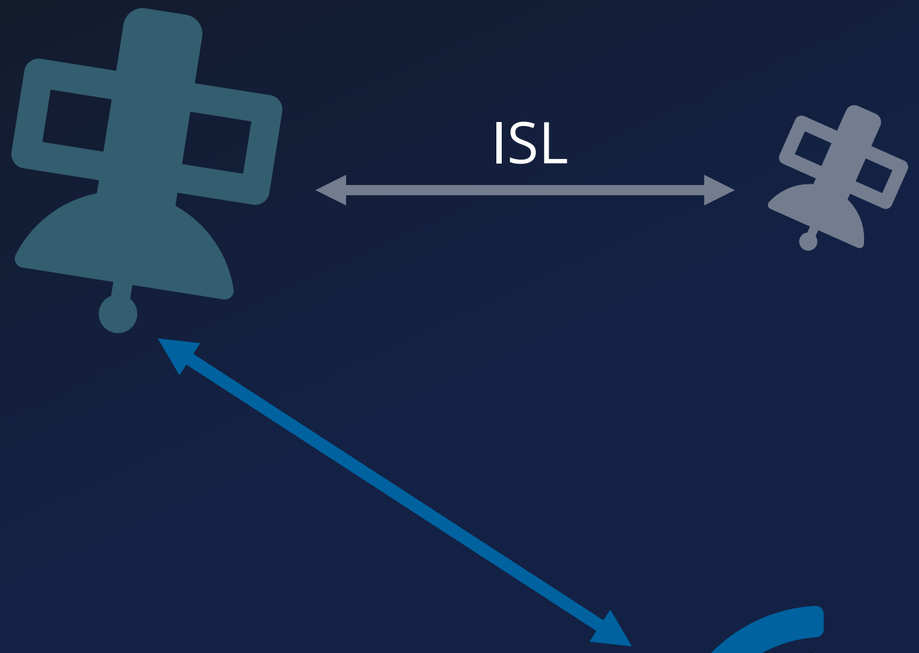


3U CubeSat



Context

Space Segment



Context

Space Segment

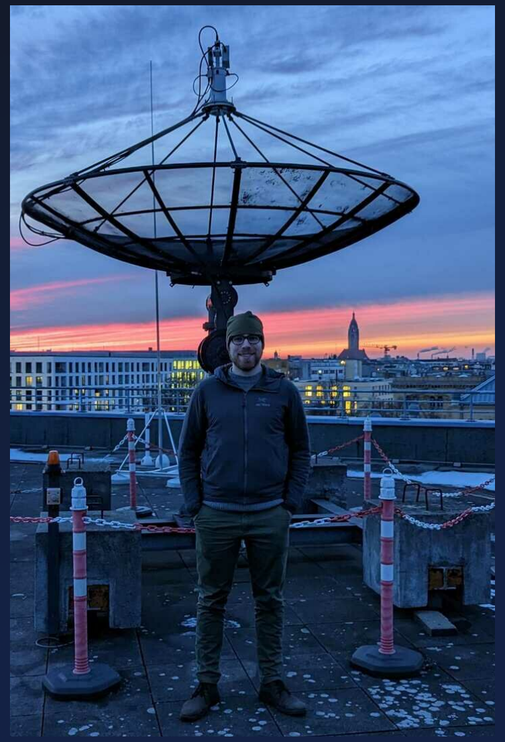
ISL

Ground Segment

Context

Space Segment

ISL



Ground Segment

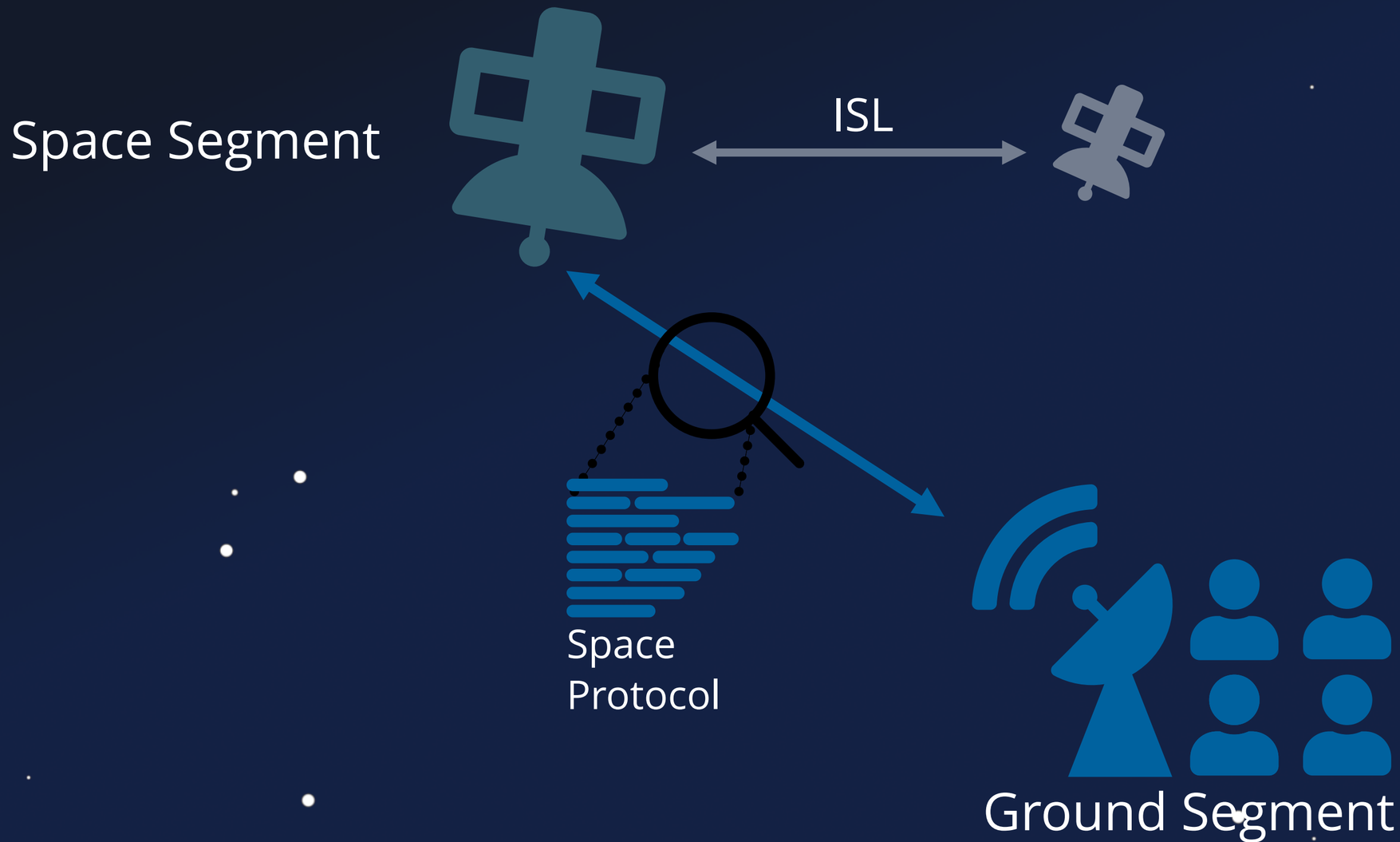
Context

Space Segment

ISL

Ground Segment

Context



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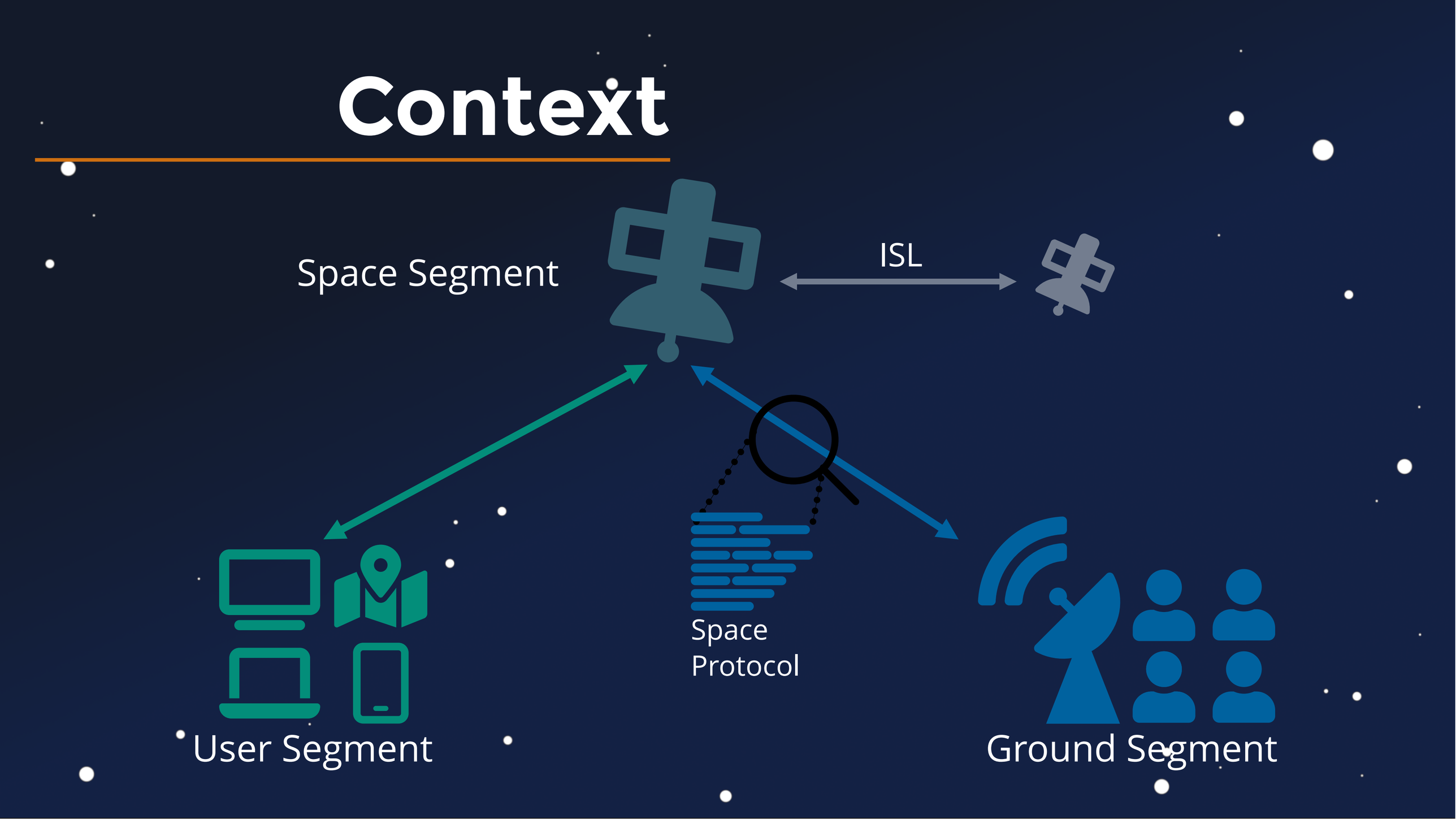

Space Segment
ISL
Space
Protocol
User Segment
Ground Segment

Our Journey ...

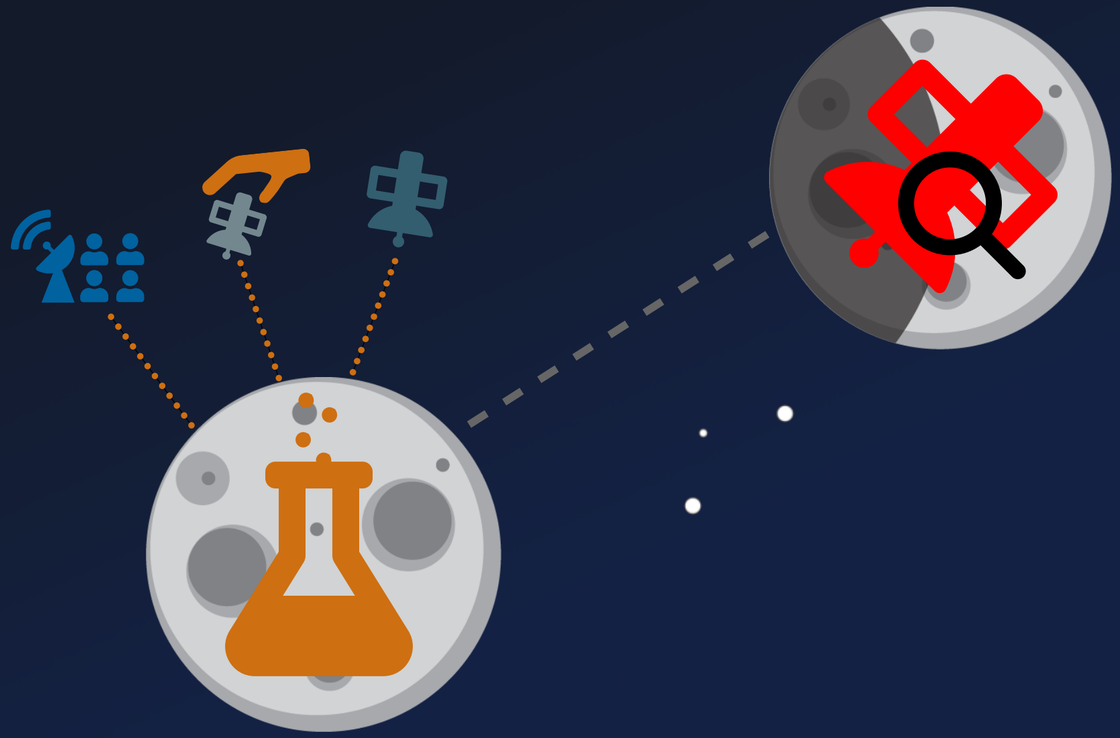
Firmware Attacks

Our Journey ...

Firmware Attacks

Our Journey ...

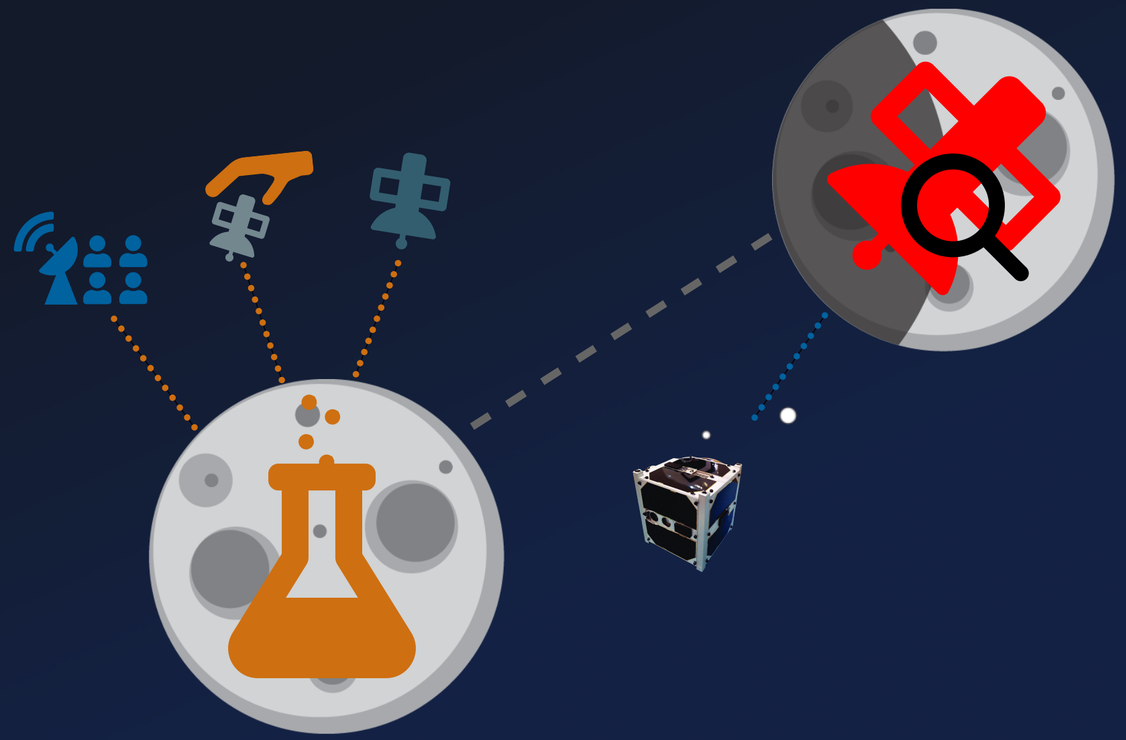
System Analysis



Firmware Attacks

Our Journey ...

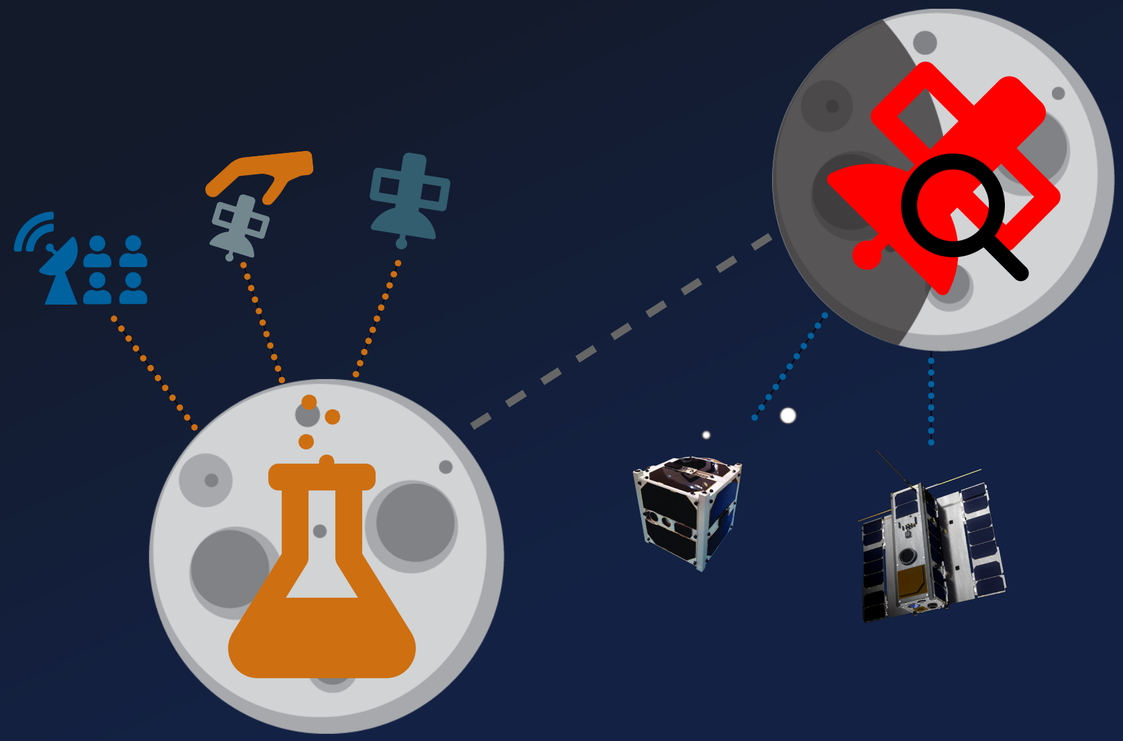
System Analysis



Firmware Attacks

Our Journey ...

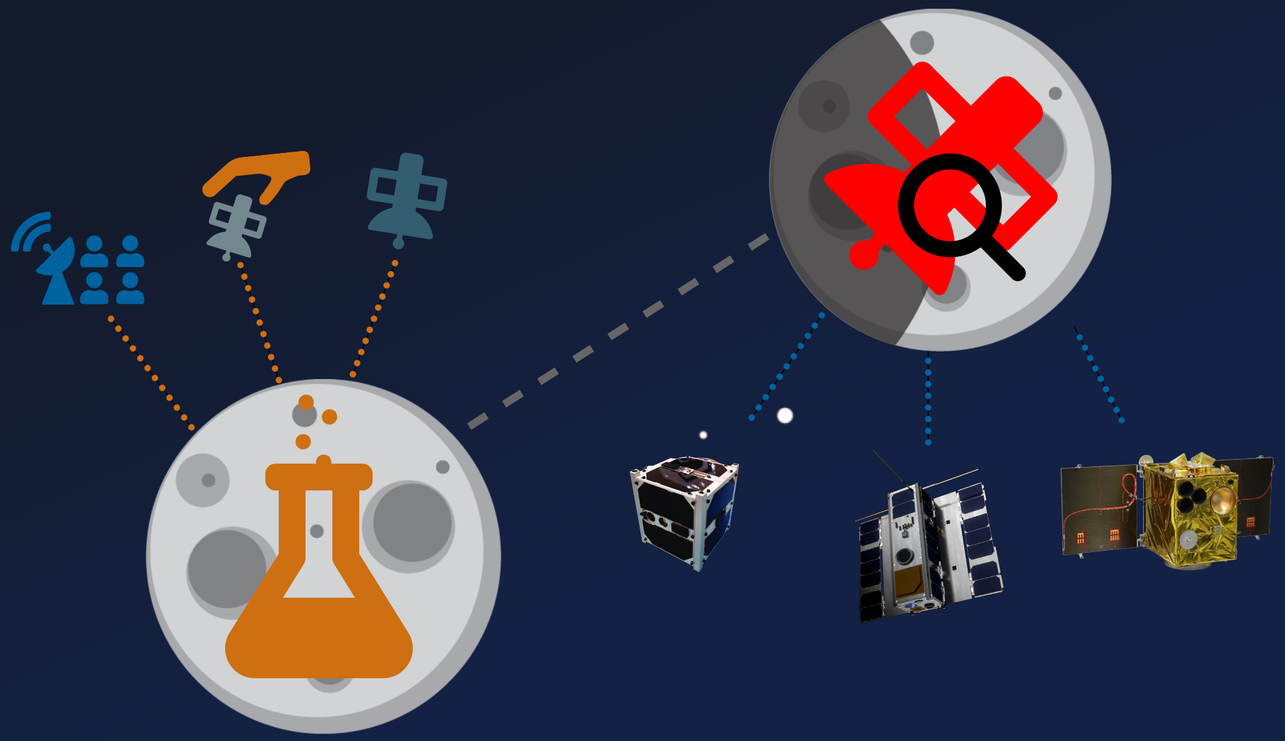
System Analysis



Firmware Attacks

Our Journey ...

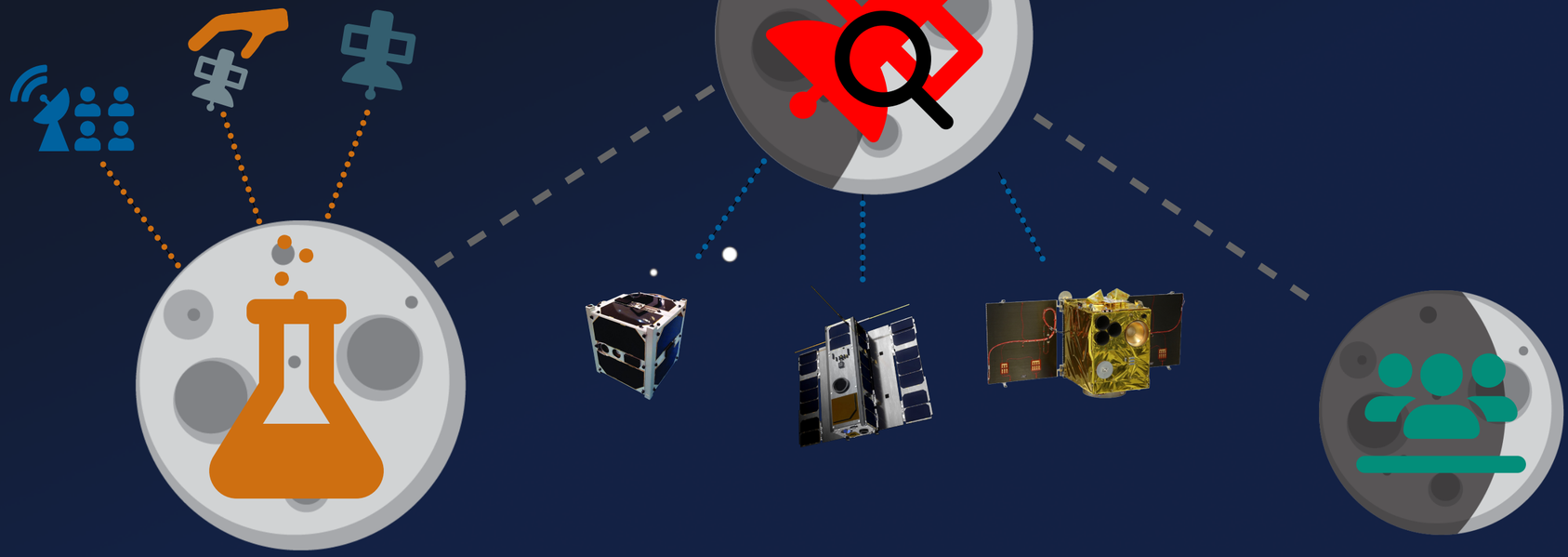
System Analysis



Firmware Attacks

Our Journey ...

System Analysis

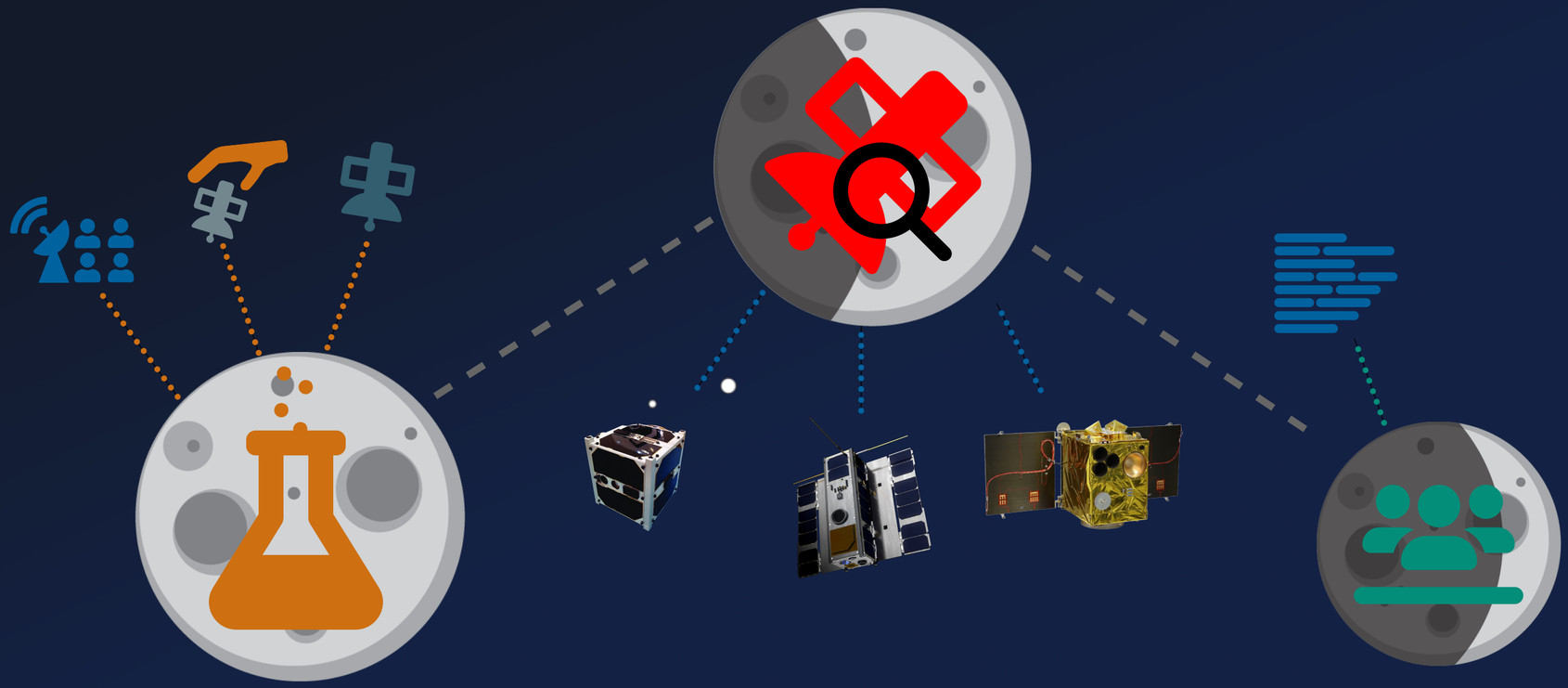


Firmware Attacks

Survey

Our Journey ...

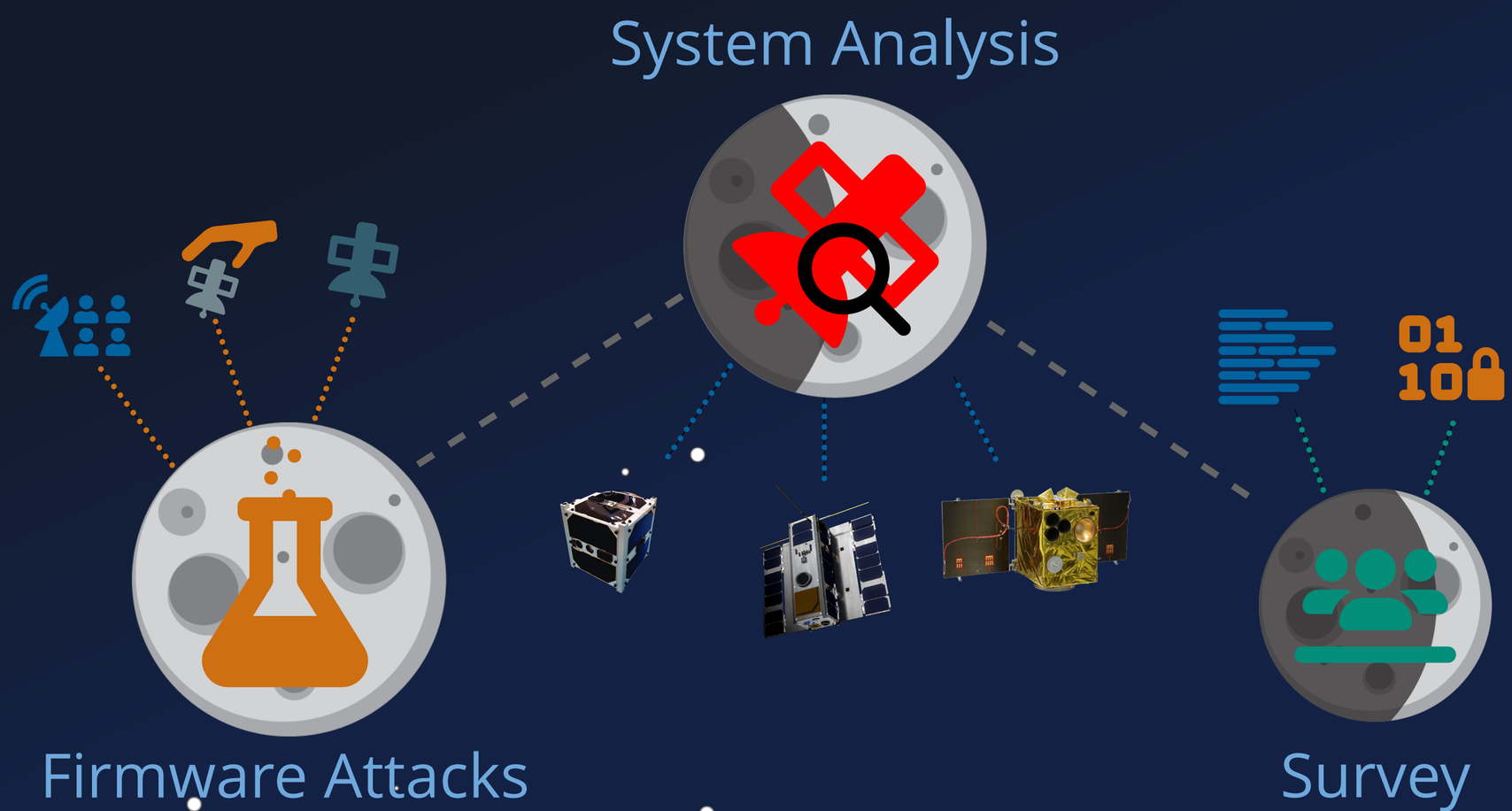
System Analysis



Firmware Attacks

Survey

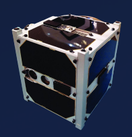
Our Journey ...

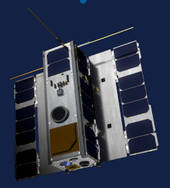


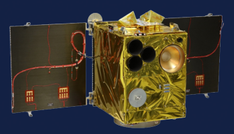
Our Journey ...

System Analysis

Attacker Perspective



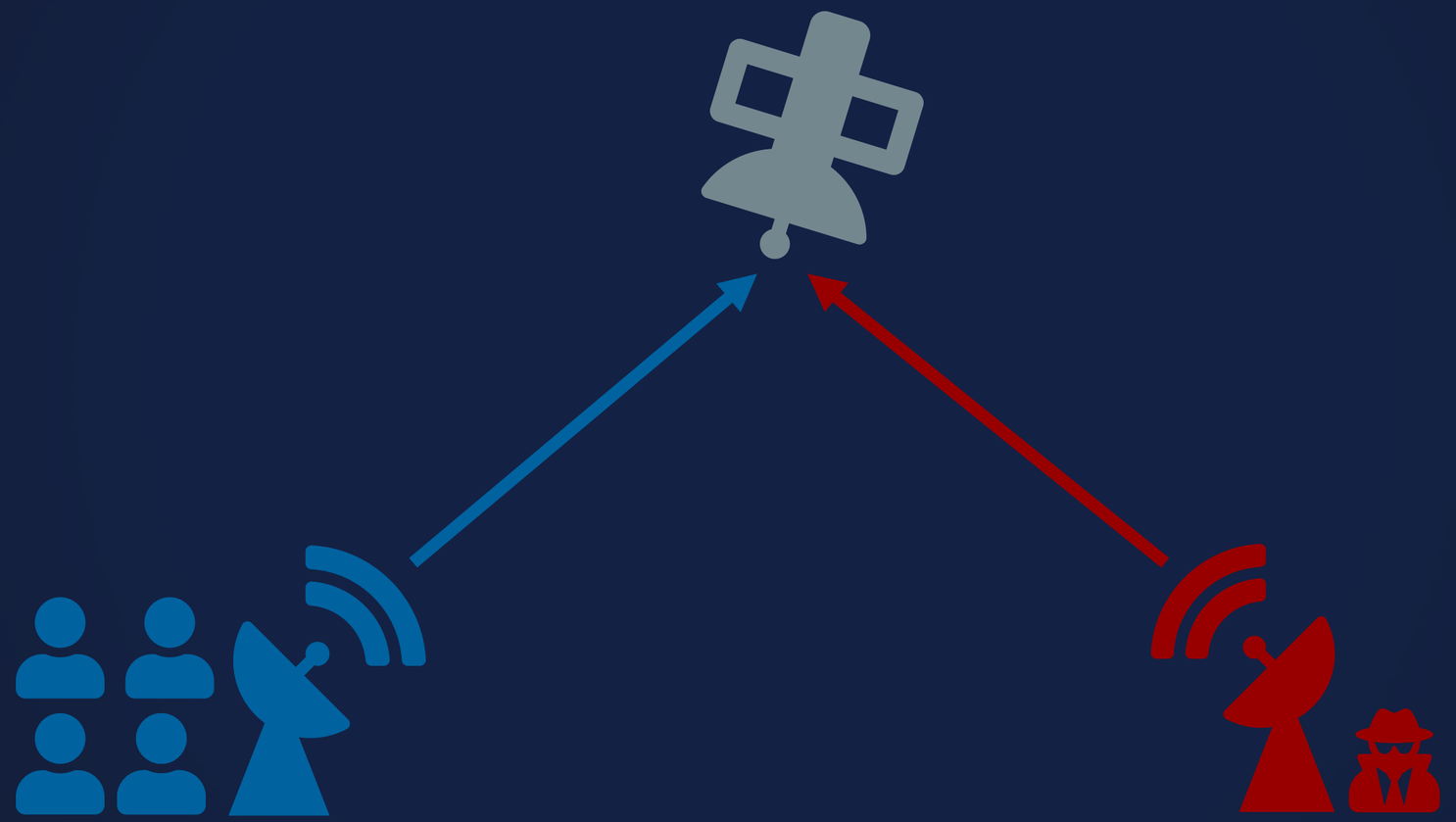




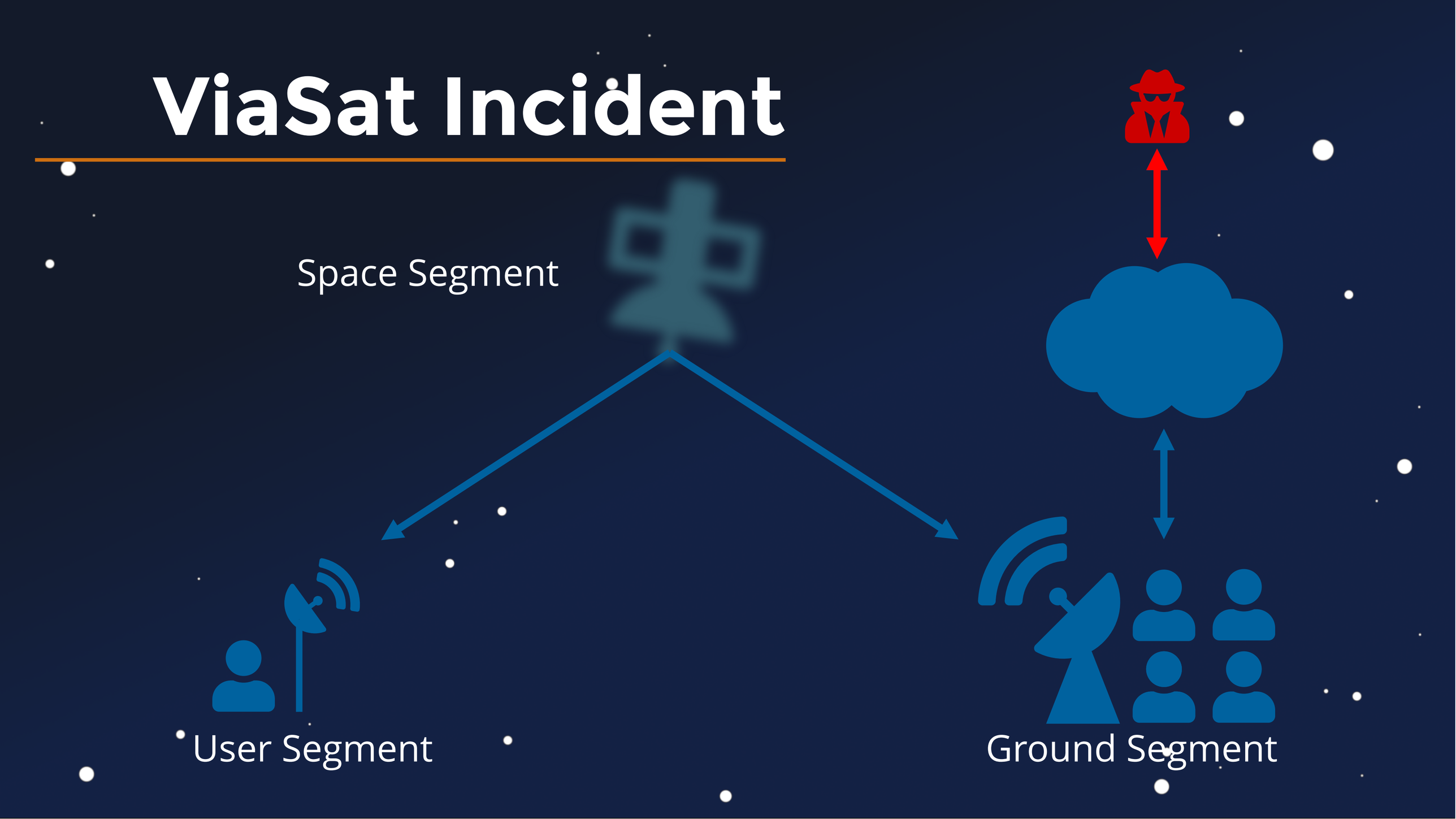
Firmware Attacks

Survey

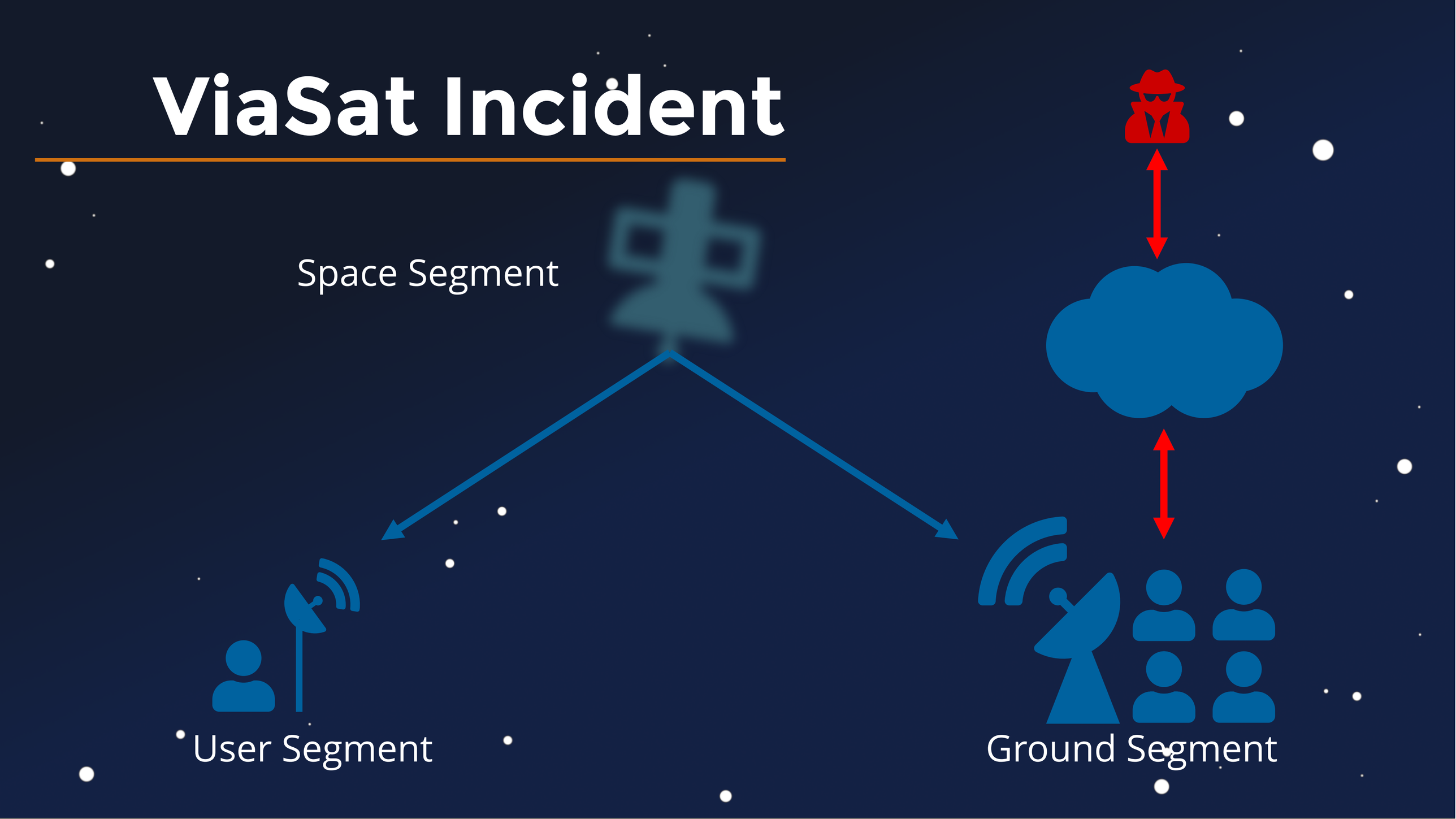
Firmware Attacks



ViaSat Incident



ViaSat Incident



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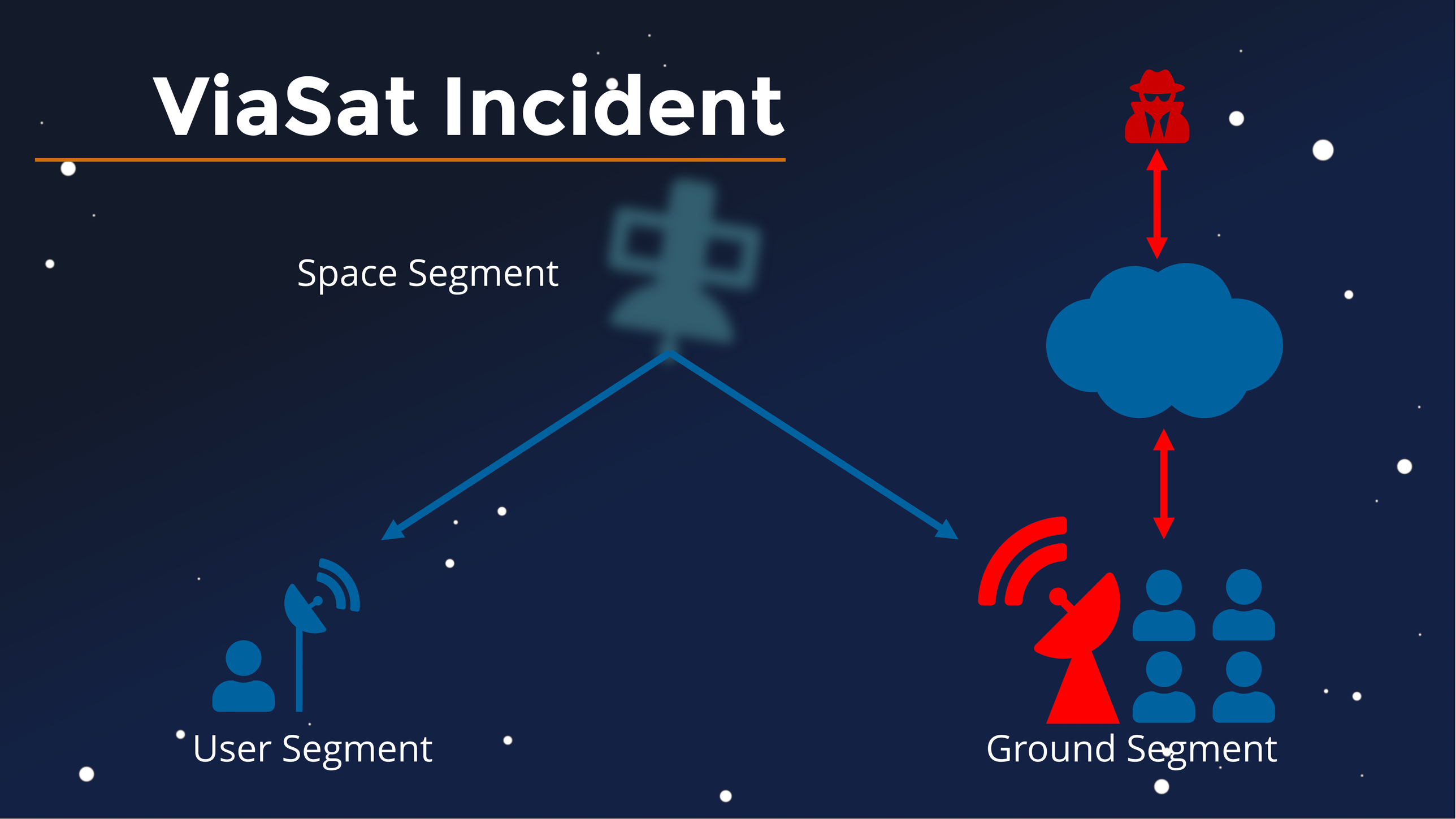

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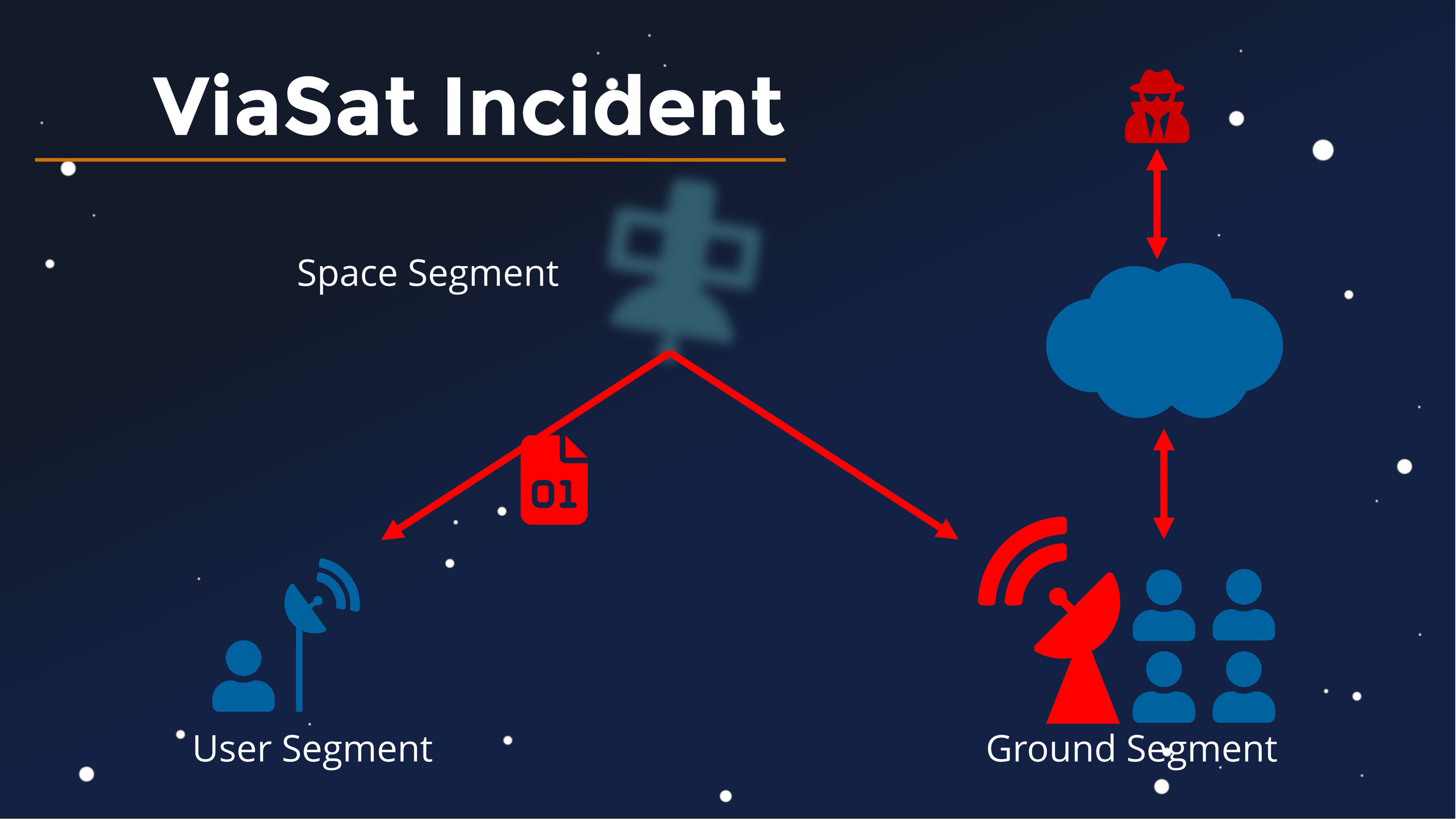

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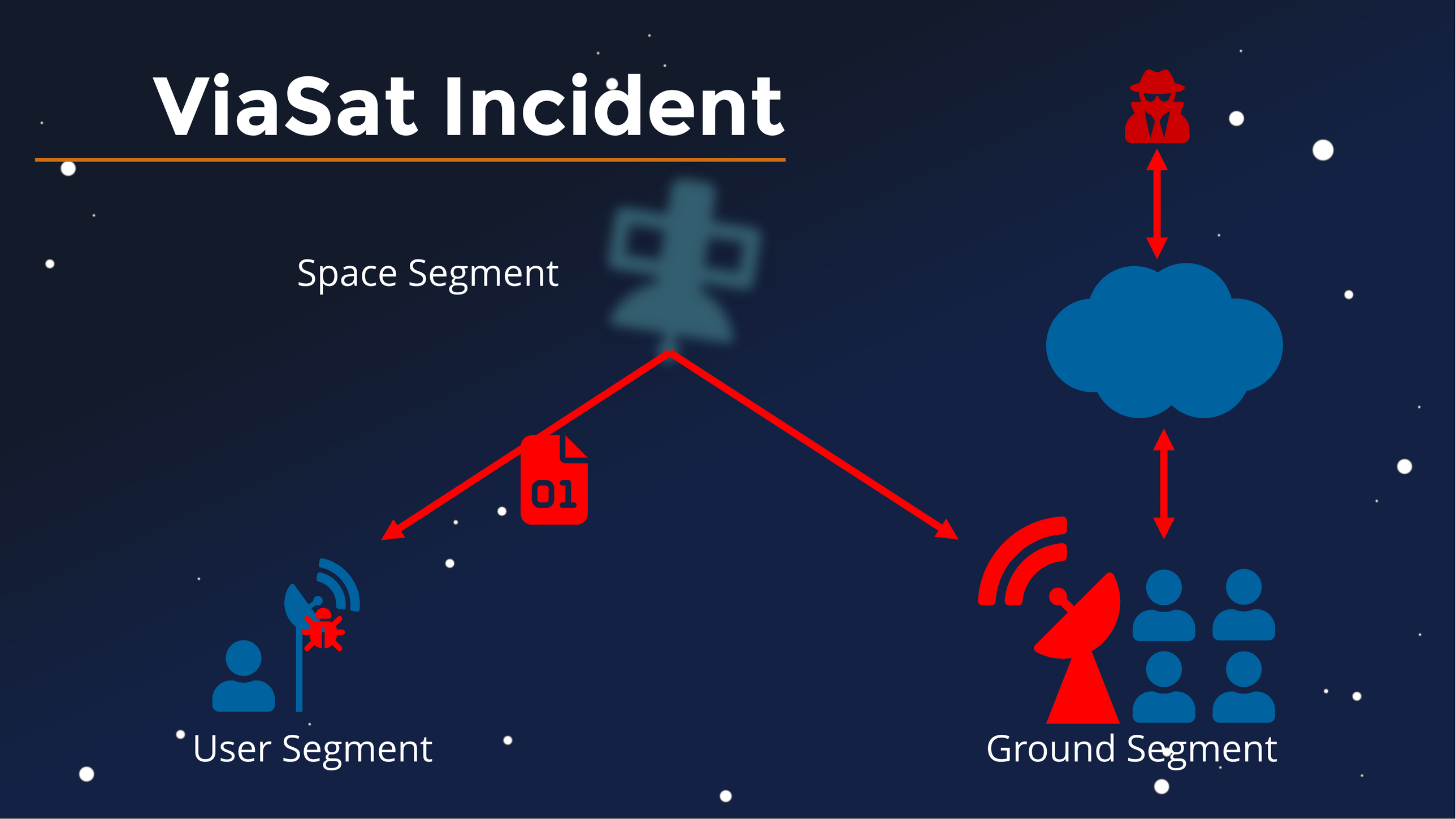
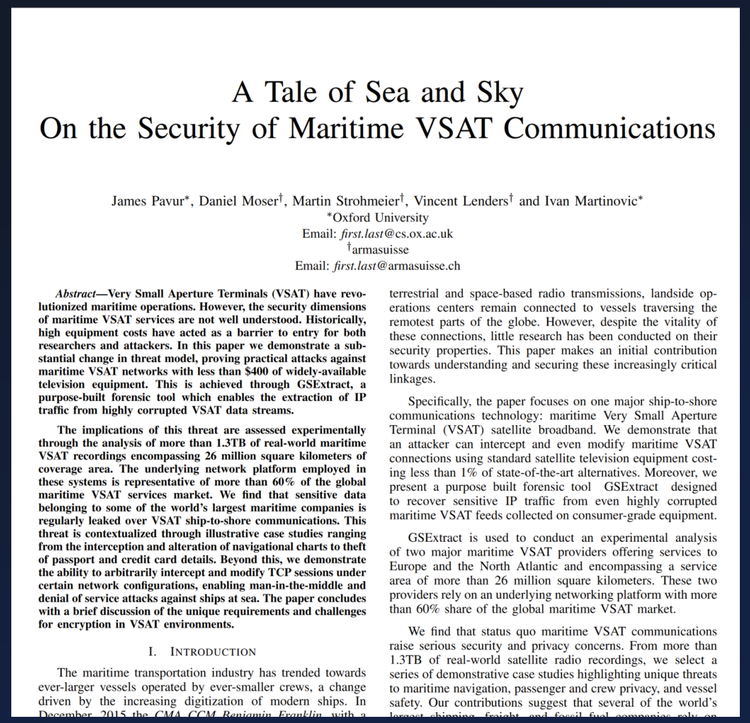


Pavur et al.



A Tale of Sea and Sky
On the Security of Maritime VSAT Communications

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***Abstract*—Very Small Aperture Terminals (VSAT) have revolutionized maritime operations. However, the security dimensions of maritime VSAT services are not well understood. Historically, high equipment costs have acted as a barrier to entry for both researchers and attackers. In this paper we demonstrate a substantial change in threat model, proving practical attacks against maritime VSAT networks with less than $400 of widely-available television equipment. This is achieved through GSExtract, a purpose-built forensic tool which enables the extraction of IP traffic from highly corrupted VSAT data streams.**

The implications of this threat are assessed experimentally through the analysis of more than 1.3TB of real-world maritime VSAT recordings encompassing 26 million square kilometers of coverage area. The underlying network platform employed in these systems is representative of more than 60% of the global maritime VSAT services market. We find that sensitive data belonging to some of the world's largest maritime companies is regularly leaked over VSAT ship-to-shore communications. This threat is contextualized through illustrative case studies ranging from the interception and alteration of navigational charts to theft of passport and credit card details. Beyond this, we demonstrate the ability to arbitrarily intercept and modify TCP sessions under certain network configurations, enabling man-in-the-middle and denial of service attacks against ships at sea. The paper concludes with a brief discussion of the unique requirements and challenges for encryption in VSAT environments.

I. Introduction

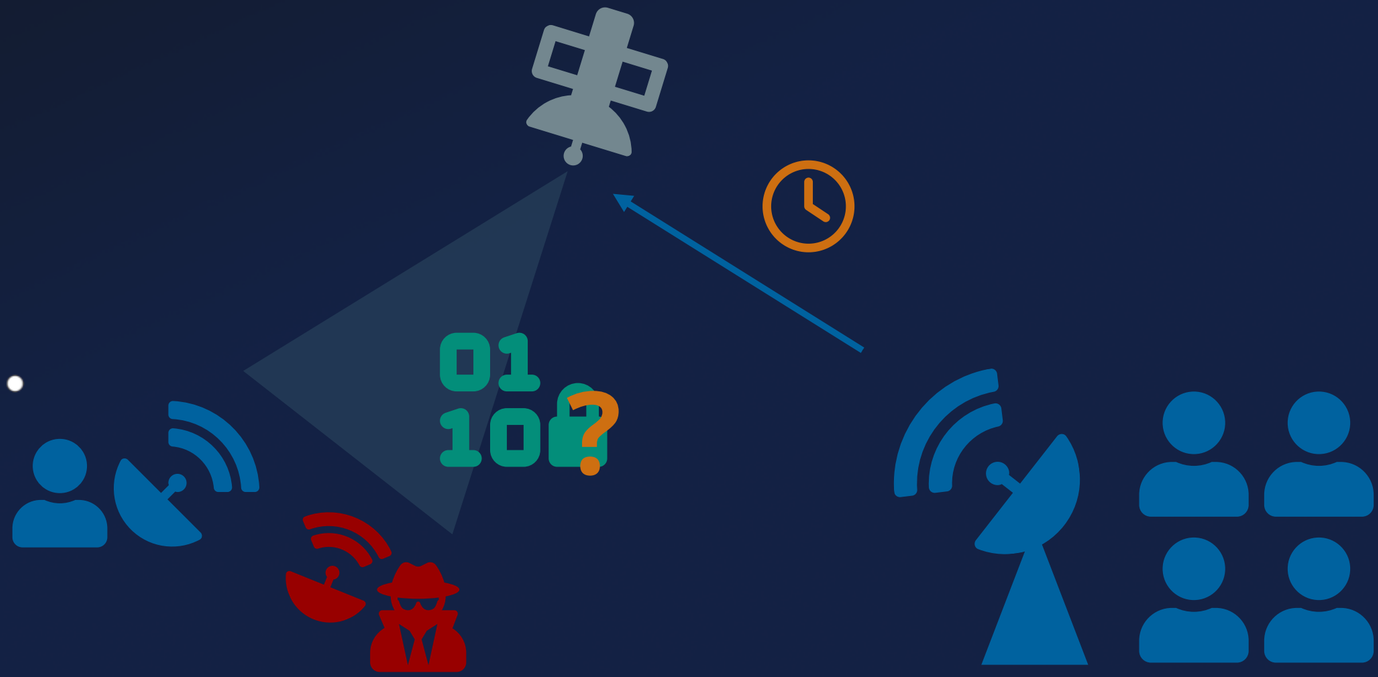
The maritime transportation industry has trended towards ever-larger vessels operated by ever-smaller crews, a change driven by the increasing digitization of modern ships. In December 2015 the *CMA CGM Benjamin Franklin* with a

terrestrial and space-based radio transmissions, landside operations centers remain connected to vessels traversing the remotest parts of the globe. However, despite the vitality of these connections, little research has been conducted on their security properties. This paper makes an initial contribution towards understanding and securing these increasingly critical linkages.

Specifically, the paper focuses on one major ship-to-shore communications technology: maritime Very Small Aperture Terminal (VSAT) satellite broadband. We demonstrate that an attacker can intercept and even modify maritime VSAT connections using standard satellite television equipment costing less than 1% of state-of-the-art alternatives. Moreover, we present a purpose built forensic tool GSExtract designed to recover sensitive IP traffic from even highly corrupted maritime VSAT feeds collected on consumer-grade equipment.

GSExtract is used to conduct an experimental analysis of two major maritime VSAT providers offering services to Europe and the North Atlantic and encompassing a service area of more than 26 million square kilometers. These two providers rely on an underlying networking platform with more than 60% share of the global maritime VSAT market.

We find that status quo maritime VSAT communications raise serious security and privacy concerns. From more than 1.3TB of real-world satellite radio recordings, we select a series of demonstrative case studies highlighting unique threats to maritime navigation, passenger and crew privacy, and vessel safety. Our contributions suggest that several of the world's



Salkield et al.

Firefly: Spoofing Earth Observation Satellite Data through Radio Overshadowing

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***Abstract*—Data from Earth Observation satellites has become crucial in private enterprises, research applications, and in coordinating national responses to events such as forest fires. These purposes are supported by data derived from a variety of satellites, some of which do not secure the wireless downlink channel effectively. This opens the door for modern adversaries to conduct spoofing attacks by overshadowing the signal with commercially available radio equipment.**

In this paper, we assess the vulnerability of current Earth Observation systems to spoofing attacks conducted at the physical layer. The effect of these attacks is amplified since the data is received at dedicated ground stations and distributed to hundreds of downstream systems, which are themselves not designed with security in mind. Specifically, we take NASA's live forest fire detection system as a case study, and demonstrate that the attacker can achieve arbitrary manipulation of fires in the derived dataset to trigger false emergency responses or mislead crisis analysis. We also assess the attack surface presented by ground station software which implicitly trusts data from the RF port. Against the NASA system we uncover several new vulnerabilities that can be exploited to stealthily deny service.

We conclude with a discussion of physical-layer countermeasures to detect and defend against spoofing, which can be implemented in existing deployments at the ground station.

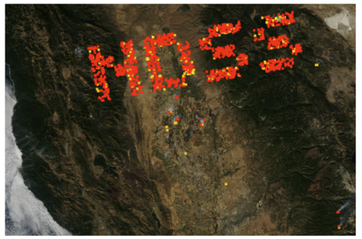

Fig. 1: An overshadowing signal from the attacker manipulates the infrared channels of satellite imagery to create fictitious fires in the resulting dataset.

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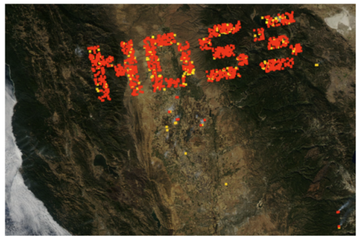

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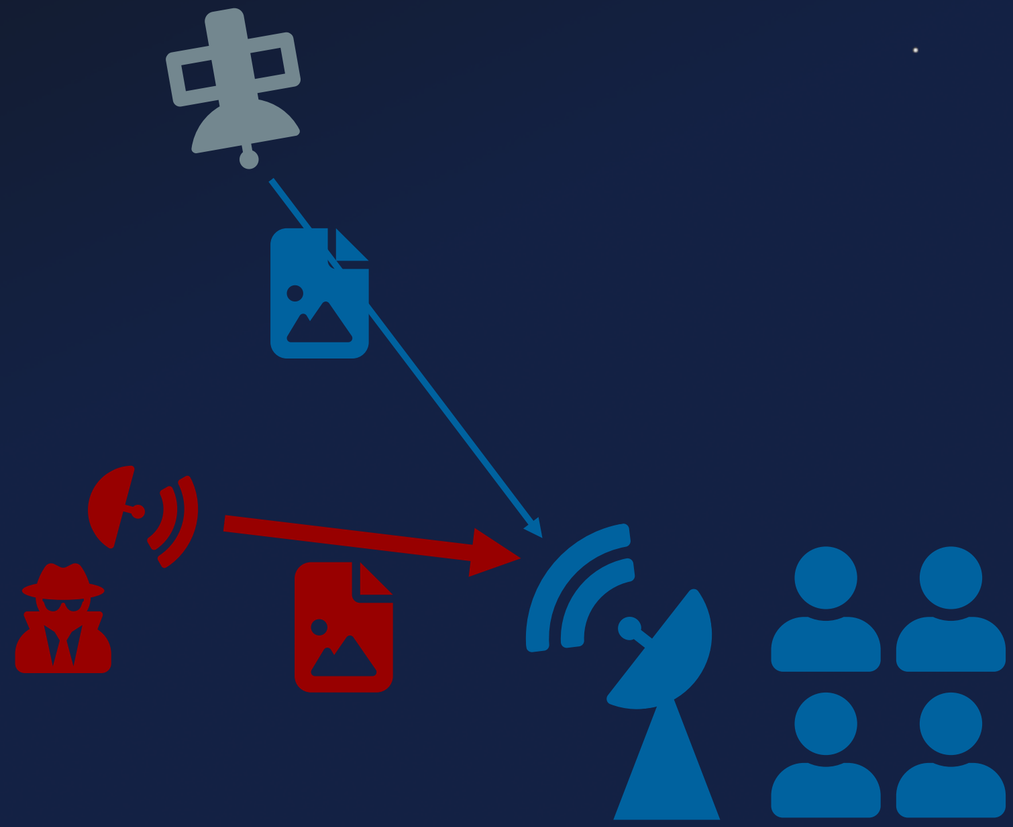

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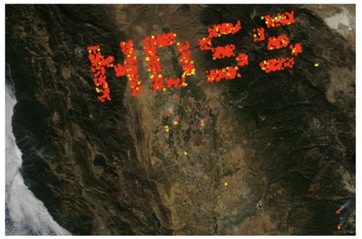

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I. Motivation

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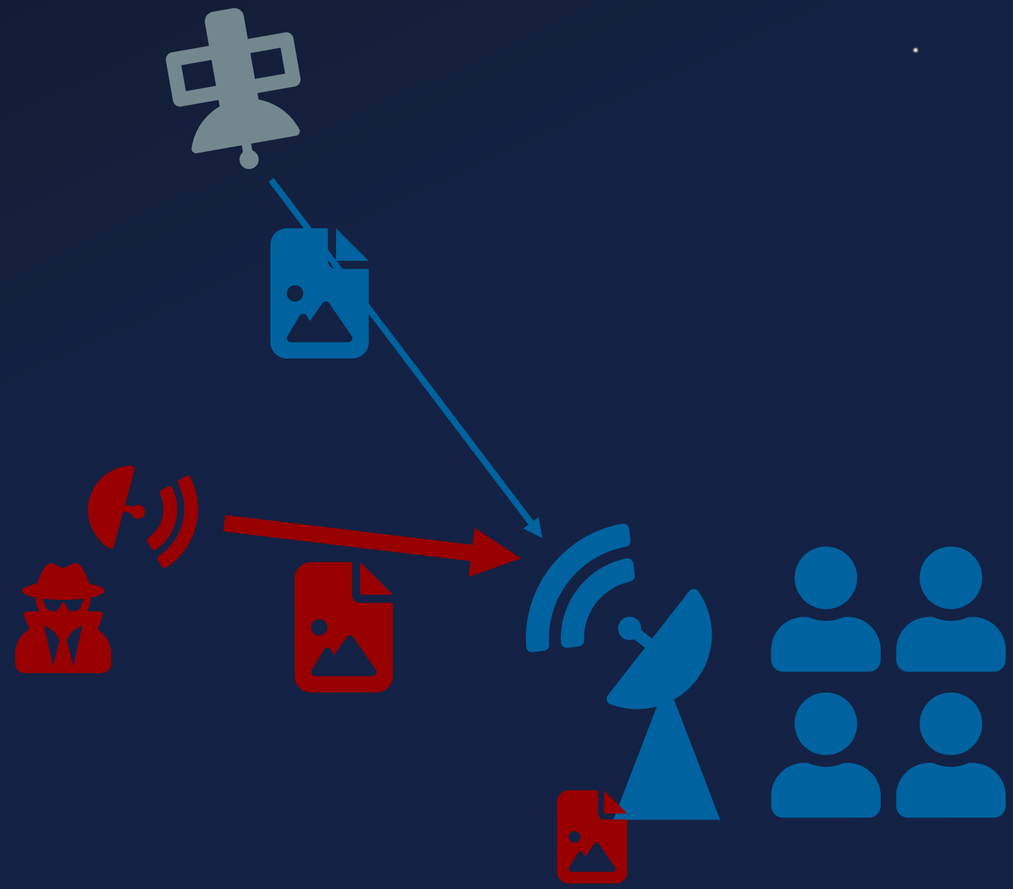
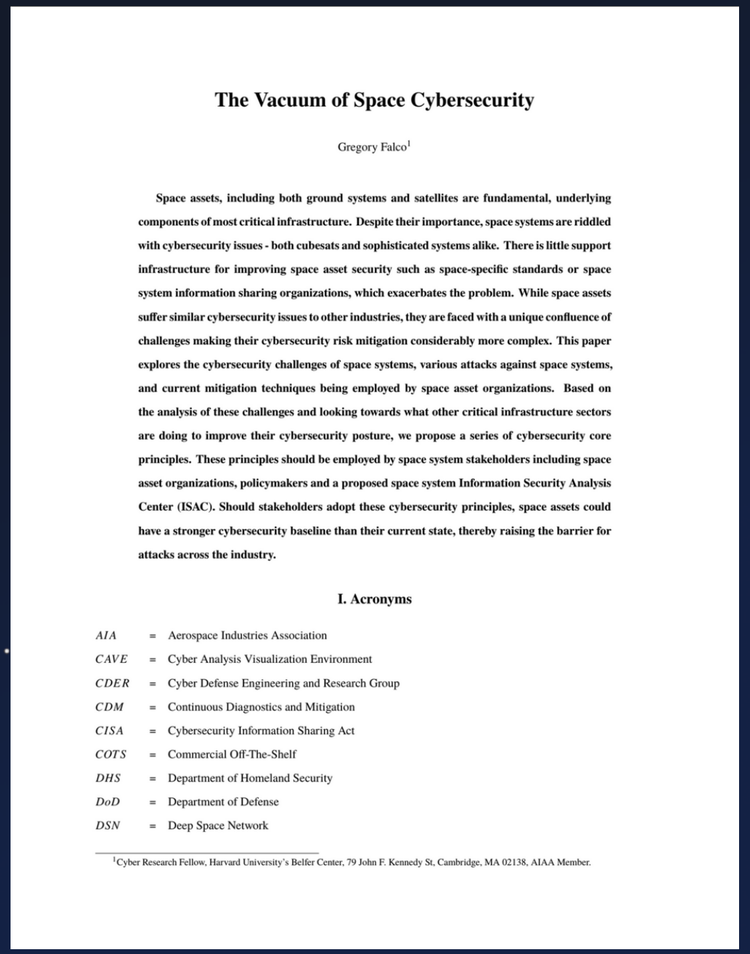
This opens the door for spoofing attacks, where an attacker can transmit a maliciously crafted radio signal to affect the



Falco



The Vacuum of Space Cybersecurity

Gregory Falco[1]

Space assets, including both ground systems and satellites are fundamental, underlying components of most critical infrastructure. Despite their importance, space systems are riddled with cybersecurity issues - both cubesats and sophisticated systems alike. There is little support infrastructure for improving space asset security such as space-specific standards or space system information sharing organizations, which exacerbates the problem. While space assets suffer similar cybersecurity issues to other industries, they are faced with a unique confluence of challenges making their cybersecurity risk mitigation considerably more complex. This paper explores the cybersecurity challenges of space systems, various attacks against space systems, and current mitigation techniques being employed by space asset organizations. Based on the analysis of these challenges and looking towards what other critical infrastructure sectors are doing to improve their cybersecurity posture, we propose a series of cybersecurity core principles. These principles should be employed by space system stakeholders including space asset organizations, policymakers and a proposed space system Information Security Analysis Center (ISAC). Should stakeholders adopt these cybersecurity principles, space assets could have a stronger cybersecurity baseline than their current state, thereby raising the barrier for attacks across the industry.

I. Acronyms

AIA	=	Aerospace Industries Association
CAVE	=	Cyber Analysis Visualization Environment
CDER	=	Cyber Defense Engineering and Research Group
CDM	=	Continuous Diagnostics and Mitigation
CISA	=	Cybersecurity Information Sharing Act
COTS	=	Commercial Off-The-Shelf
DHS	=	Department of Homeland Security
DoD	=	Department of Defense
DSN	=	Deep Space Network

[1]Cyber Research Fellow, Harvard University's Belfer Center, 79 John F. Kennedy St, Cambridge, MA 02138, AIAA Member.

1. Single Point of Failure for Industries
2. Lack of Standards/Regulations for Space Cybersecurity
3. Complex Supply Chain and Lifecycle
4. Widespread Use of COTS Software
5. Highly Specialized Workforce
6. Resource Constraints (Technical and Financial)

SpaceSec'23

Workshop on Security of Space and Satellite Systems (SpaceSec) 2023 Program

Find the updated information on workshop's website: https://easychair.org/smart-program/SpaceSec23/

Hide All

Proceedings Frontmatter

Monday, 27 February

13:30 - 13:35	Session 1: Welcome	Cockatoo Room
13:35 - 14:20	Keynote by James Pavur	Cockatoo Room
14:20 - 15:00	**Session 2 (Threat Modelling)**	**Cockatoo Room**

Cybersecurity of COSPAS-SARSAT and EPIRB: threat and attacker models, exploits, future research — Paper

Andrei Costin, Hannu Turtiainen, Syed Khandkher and Timo Hamalainen (Faculty of Information Technology, University of Jyvaskyla, Finland)

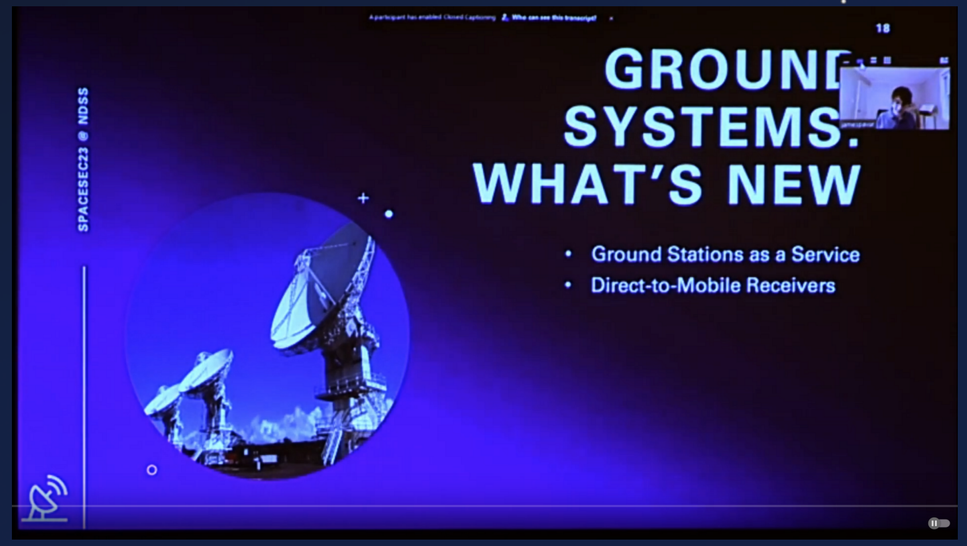
Presenter: Andrei Costin

+ Abstract

Position Paper: Space System Threat Models Must Account for Satellite Sensor Spoofing — Paper

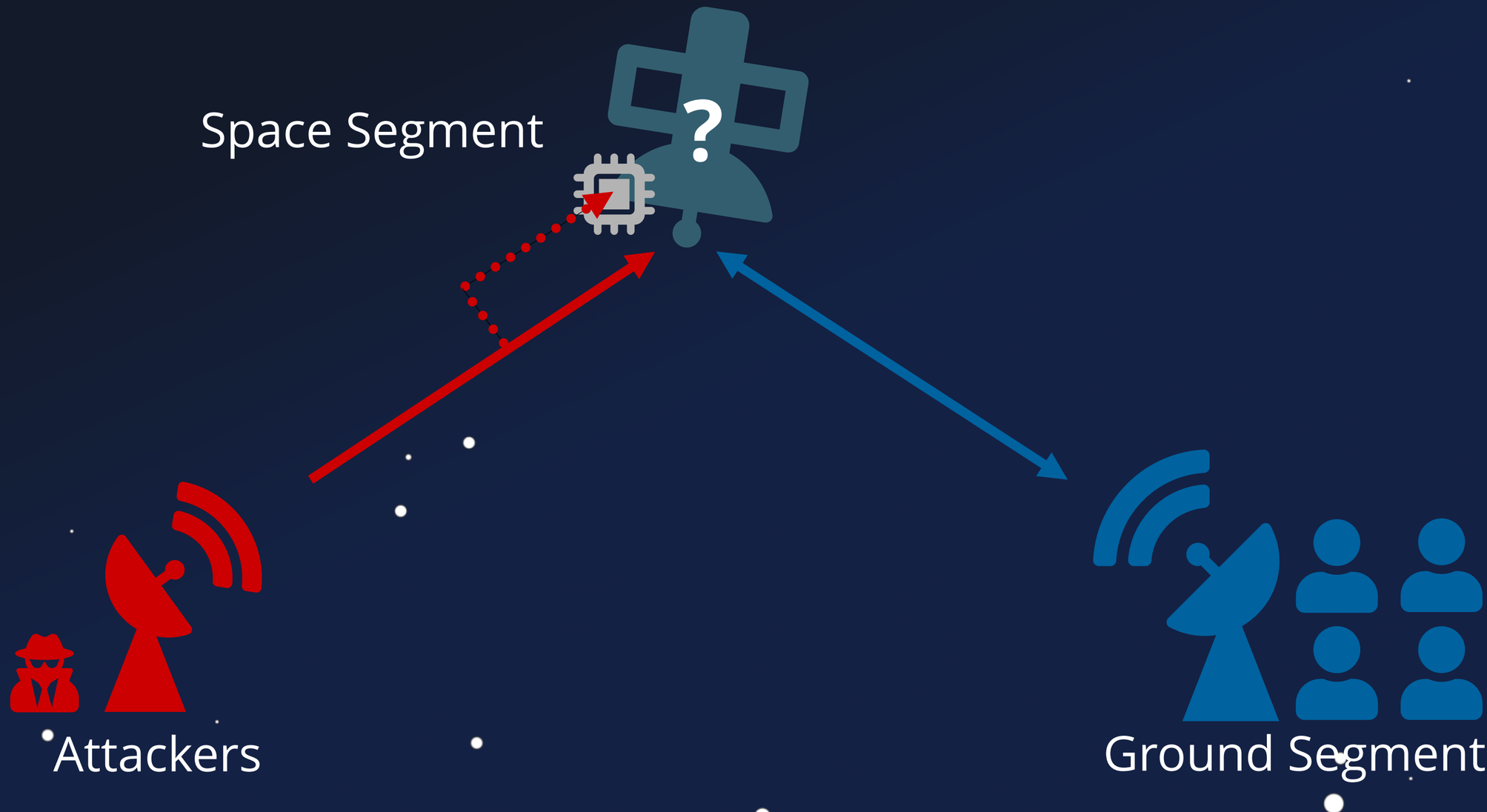
Benjamin Cyr and Yan Long (University of Michigan), Takeshi Sugawara (The University of Electro-Communications), Kevin Fu (Northeastern University)

+ Abstract



SpaceSec 2023 - Keynote
Securing the Cosmos: On the Future of Space Systems Security Research

Firmware Attacks



Not so Novel


CCSDS
The Consultative Committee for Space Data Systems
Report Concerning Space Data System Standards
SECURITY THREATS AGAINST SPACE MISSIONS
INFORMATIONAL REPORT
CCSDS 350.1-G-3
GREEN BOOK
February 2022

Not so Novel

3.4.8 REPLAY

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Description: Transmissions to or from a spacecraft or between ground system computers can be intercepted, recorded, and played back at a later time.

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Not so Novel

CCSDS REPORT CONCERNING SECURITY THREATS AGAINST SPACE MISSIONS

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MARCH 2020

A REPORT OF THE CSIS AEROSPACE SECURITY PROJECT

SPACE THREAT ASSESSMENT 2020

Authors
TODD HARRISON
KAITLYN JOHNSON
THOMAS G. ROBERTS
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MAKENA YOUNG

Foreword
MARTIN C. FAGA

CSIS | CENTER FOR STRATEGIC & INTERNATIONAL STUDIES

Not so Novel

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CCSDS 350.1-G-3 Page 3-8 February 2022

MARCH 2020

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Foreword
MARTIN C

CSIS

Illustration
Cyberattacks can be used to take control of a satellite and damage or destroy it.

user terminals that connect to satellites are all potential intrusion points for cyberattacks. Cyberattacks can be used to monitor data traffic patterns (i.e., which users are communicating), to monitor the data itself, or to insert false or corrupted data in the system. While cyberattacks require a high degree of understanding of the systems being targeted, they do not necessarily require significant resources to conduct. Cyberattacks can be contracted out to private groups or individuals, which means that a state or non-state actor that lacks internal cyber capabilities may still pose a cyber threat.[3]

A cyberattack on space systems can result in data loss, widespread disruptions, and even permanent loss of a satellite. For example, if an adversary can seize control of a satellite through a cyberattack on its command and control system, the attack could shut down all communications and permanently damage the satellite by expending its propellant supply or damaging its electronics and sensors. Accurate and timely attribution of a cyberattack can be difficult, if not impossible, because attackers can use a variety of methods to conceal their identity, such as using hijacked servers to launch an attack.

THREAT CHARACTERISTICS

The types of counterspace threats described above have distinctly different characteristics that make them more suitable for use in some scenarios than others. As shown in Table 1, some types of counterspace threats are difficult to attribute or have fully reversible effects, such as mobile jammers. High-powered lasers, for example, are "silent" and can carry out an attack with little public awareness that anything has happened. Other types of counterspace weapons produce effects that make it difficult for the attacker to know if the attack was successful, and some produce collateral damage that can affect space systems other than the one being targeted.

Counterspace weapons that are reversible, difficult to attribute, and have limited public awareness are ideally suited for situations in which an opponent may want to signal resolve, create uncertainty in the mind of its opponent, or achieve a fait accompli without triggering an escalatory response. For example, an adversary that wants to deter the United States from intervening in a situation may believe that such attacks will stay below the threshold for escalation (i.e., not trigger the very thing it is trying to prevent) while creating significant operational challenges for the United States that make the prospect of intervention more costly and protracted. Conversely, counterspace weapons that have limited battle damage assessment or that risk collateral damage may be less useful to adversaries in many situations. Without reliable battle damage assessment, for example, an adversary cannot plan operations with the confidence that its counterspace actions have been successful. Furthermore, weapons that produce collateral damage in space, such as large amounts of space debris, run the risk of escalating a conflict and turning other nations against the attacker.

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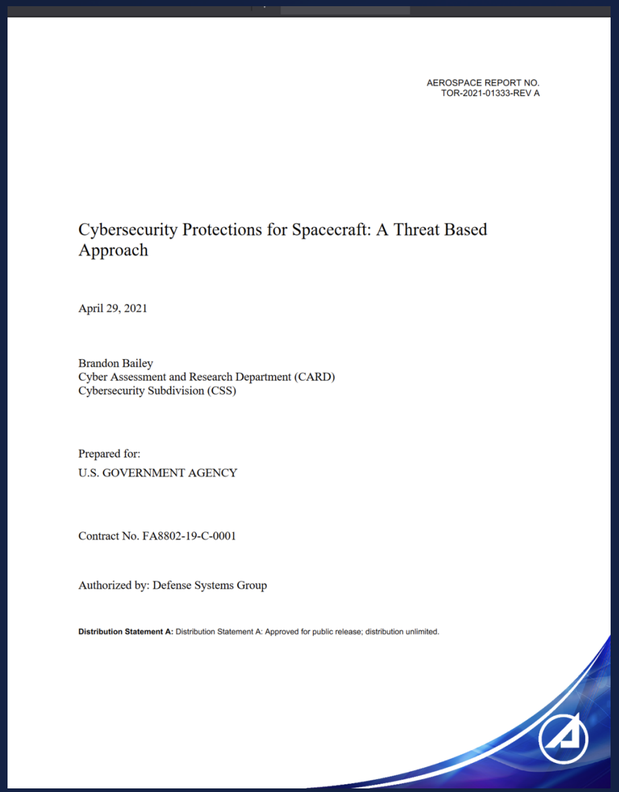

AEROSPACE REPORT NO.
TOR-2021-01333-REV A

Cybersecurity Protections for Spacecraft: A Threat Based Approach

April 29, 2021

Brandon Bailey
Cyber Assessment and Research Department (CARD)
Cybersecurity Subdivision (CSS)

Prepared for:
U.S. GOVERNMENT AGENCY

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Authorized by: Defense Systems Group

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Outdated Assumptions

Myth of Inaccessibility

$$$ → $

Affordable
Ground Stations

Myth of Inaccessibility

$$$ → $

Affordable
Ground Stations

Ground Station as a Service
GSaaS

Myth of Inaccessibility

$$$ → $

Affordable
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More Satellites
GEO → LEO

Security by Obscurity

“ No Insights <=> No Attacker

Security by Obscurity

> *~~No Insights <=> No Attacker~~*

Security by Obscurity

> *~~No Insights <=> No Attacker~~*

More Developers

More People Involved

Security by Obscurity

> ~~*No Insights <=> No Attacker*~~

More Developers
More People Involved

Commercial off-the-Shelf
(COTS)
Components

Security by Obscurity

> ~~*No Insights <=> No Attacker*~~

More Developers
More People Involved

Commercial off-the-Shelf
(COTS)
Components

Higher Stakes
Critical Infrastructure

Attacker Goals

Denial of Service

Attacker Goals

Denial of Service

Malicious Data Interaction

Attacker Goals

Denial of Service

Seizure of Control

Malicious Data Interaction

Attacker Goals

Denial of Service

Seizure of Control

Malicious Data Interaction

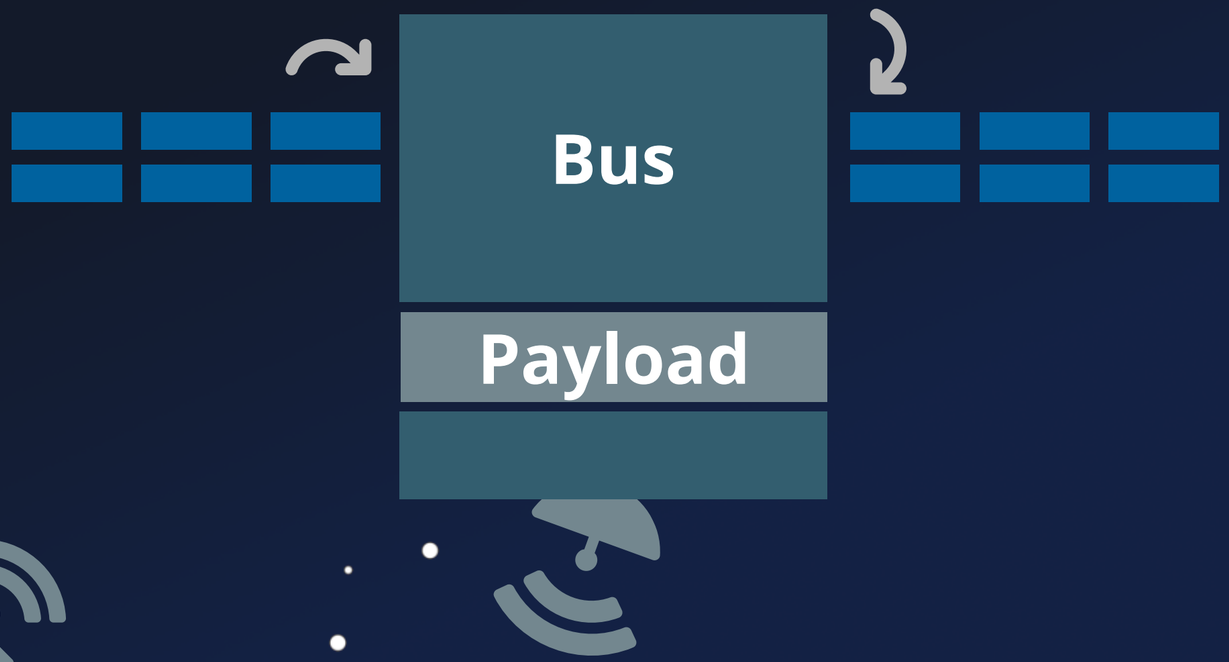
Attacker Goals

Seizure of Control

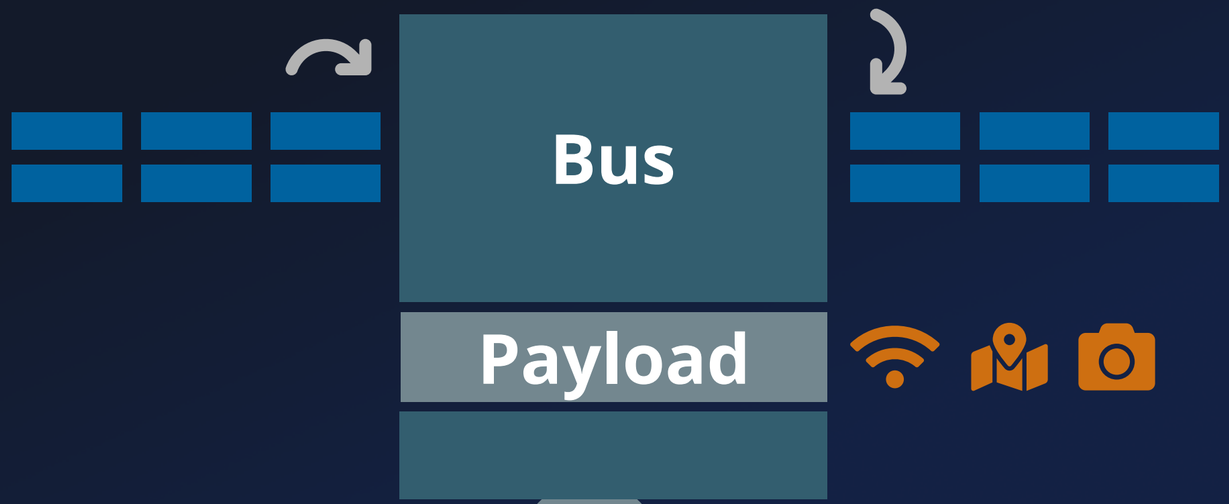
Attacker Goals

Seizure of Control

Components



Components



Components

Components

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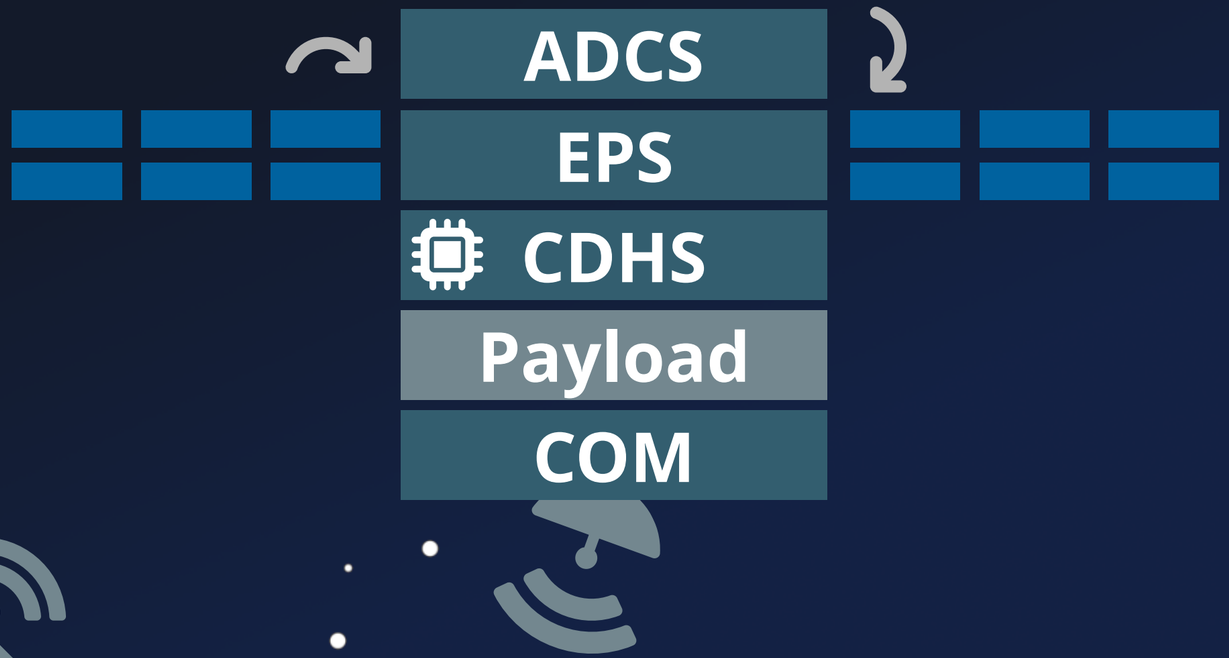

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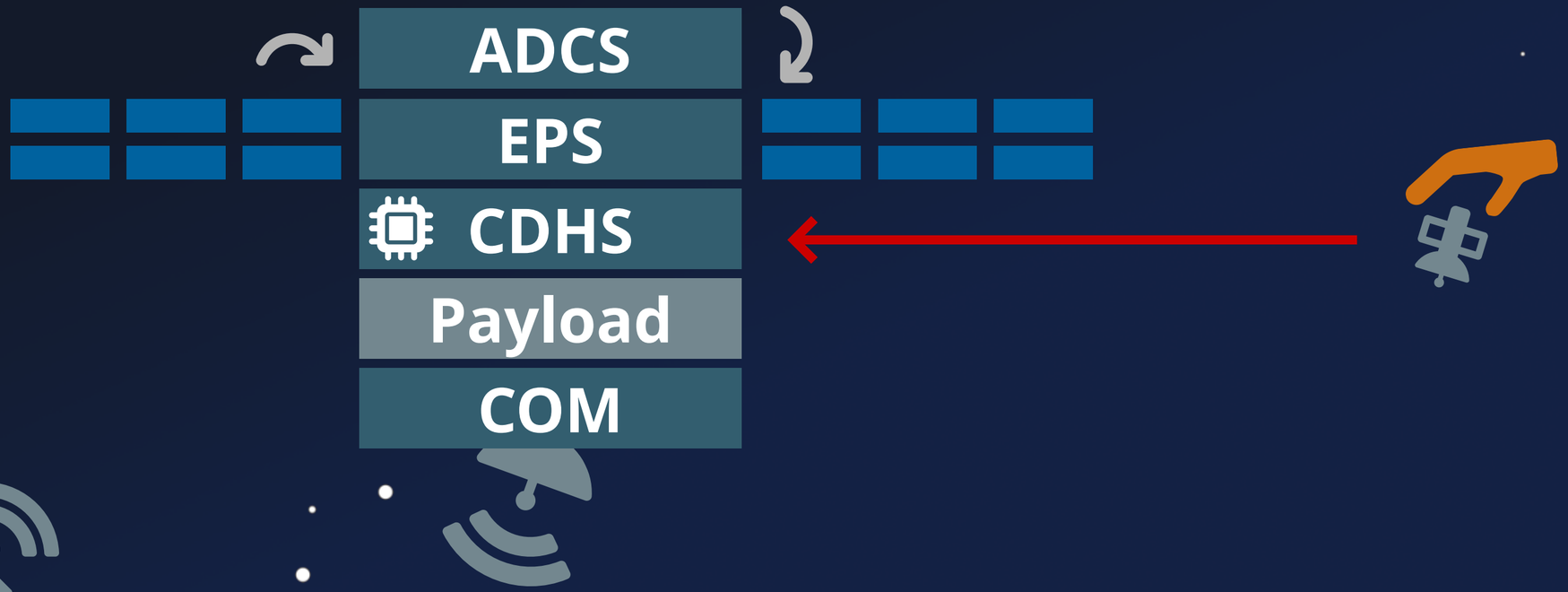


TC / TM Flow

Telecommand (TC)

Telemetry (TM)

COM

- Decode
- Authenticate
- Repackage

CDHS

- Parse
- Execute
- Respond

ADCS

EPS

Payload

TC / TM Flow

TC / TM Traffic

COM

- Decode
- Authenticate
- Repackage

CDHS

- Parse
- Execute
- Respond

ADCS

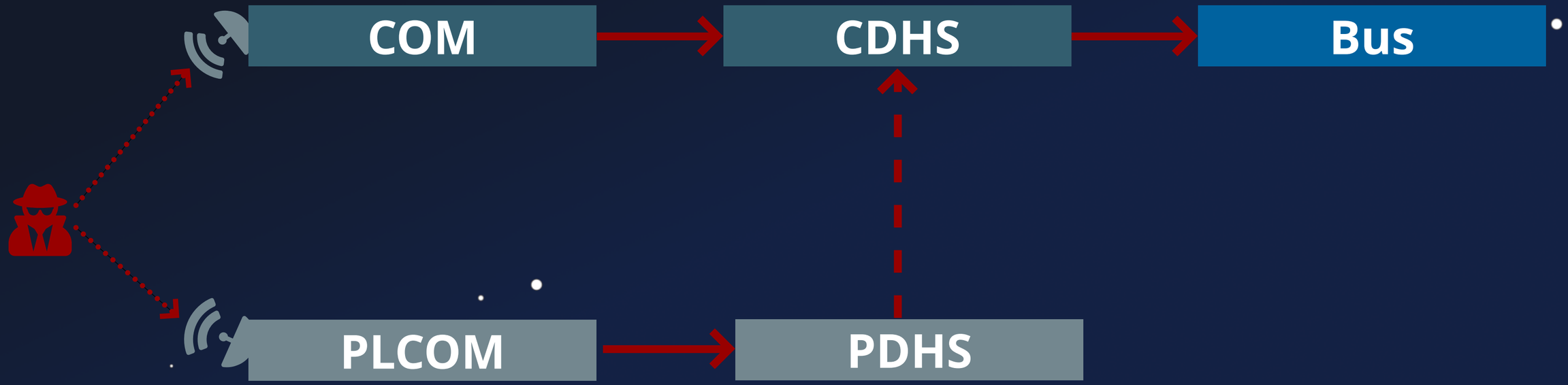
EPS

Payload Traffic

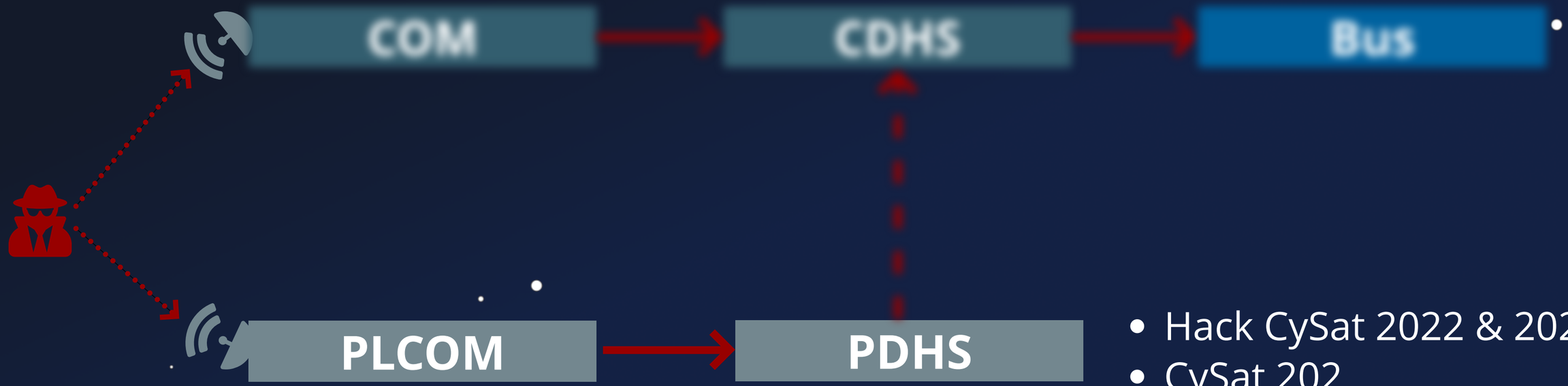
PLCOM

PDHS

Attack Path

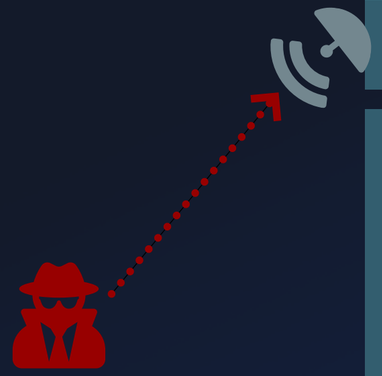


Attack Path



- Hack CySat 2022 & 2023
- CySat 202

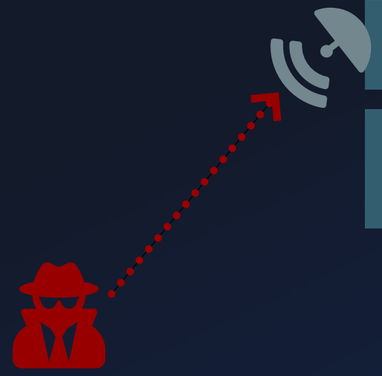
Attack Path



COM → **CDHS** → **Bus**

- Bypass COM Protection
  - Missing AC
  - Insecure Protocol
  - Outdated Crypto
  - Timing Side Channels
  - Leaked Keys
  - Timed Backdoor
  - ...

Attack Path



COM

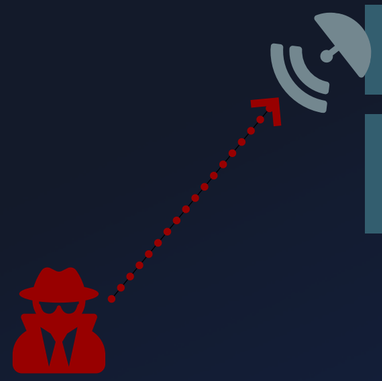
- Bypass COM Protection
  - [...]

CDHS

- Deploy Attacker Payload
  - Firmware Update
    - Signed Image
    - Slow Upload
    - Complex System

Bus

Attack Path



COM

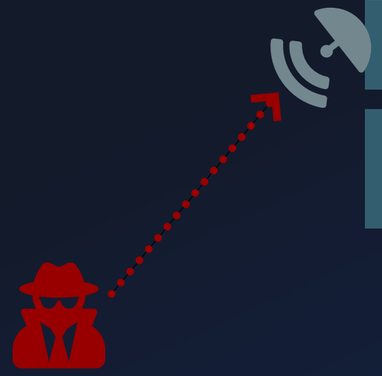
- Bypass COM Protection
  - [...]

CDHS

- Deploy Attacker Payload
  - ~~Firmware Update~~
  - Dangerous TC
  - Vulnerable TC

Bus

Attack Path



COM

- Bypass COM Protection
  - [...]

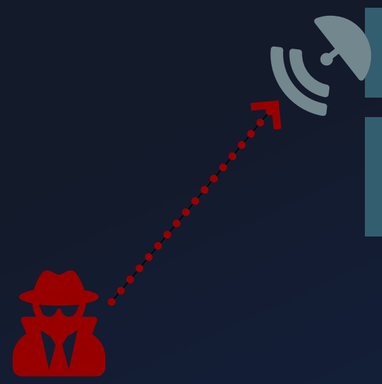
CDHS

- Deploy Attacker Payload
  - ~~Firmware Update~~
  - Dangerous TC
  - Vulnerable TC

Bus

- Hijack Bus Control Flow
- Full Bus Privileges

Attack Path



COM

- Bypass COM Protection
  - [...]

CDHS

- Deploy Attacker Payload
  - ~~Firmware Update~~
  - Dangerous TC
  - Vulnerable TC

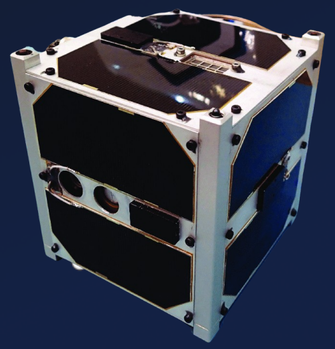
Bus

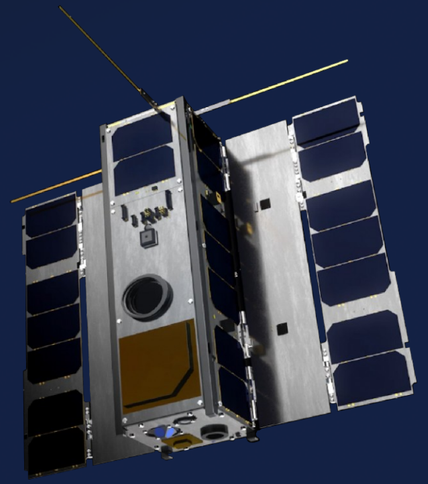
- Hijack Bus Control Flow
- Full Bus Privileges

Objectives

1. Bypass COM Protection
2. Dangerous / Vulnerable TC
3. Hijack Bus Control Flow
4. Full Bus Privileges

Satellite Case Studies





Approach

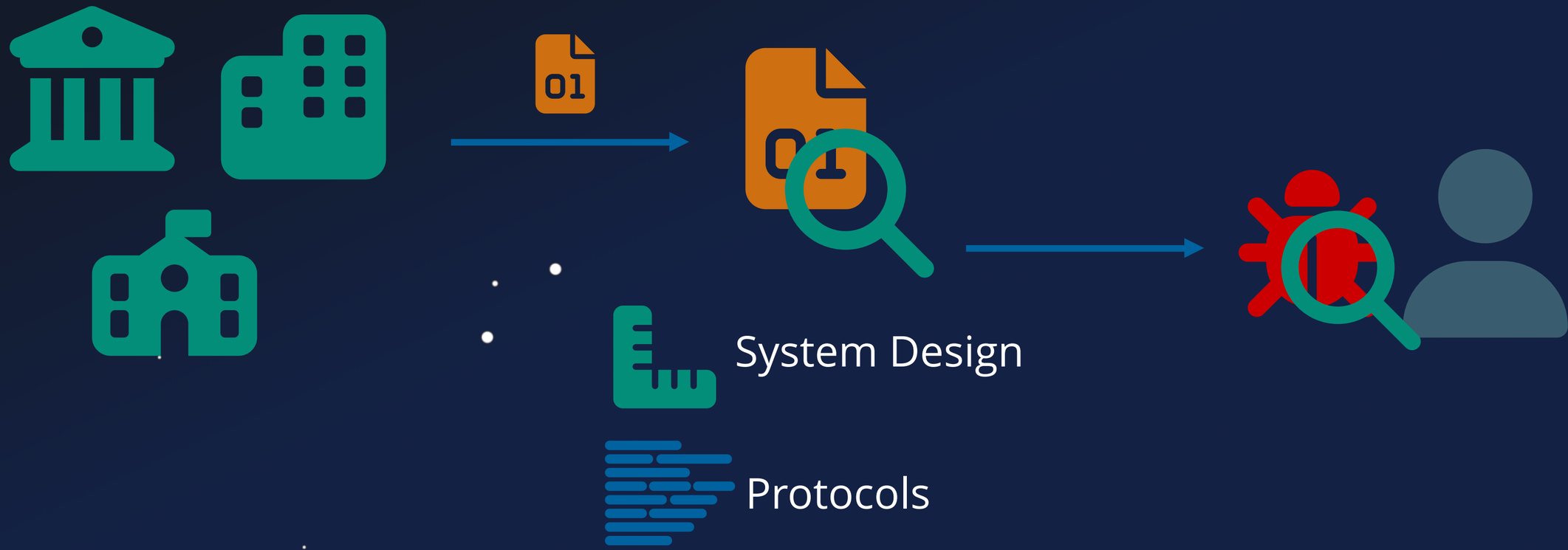
Approach

Approach

System Design

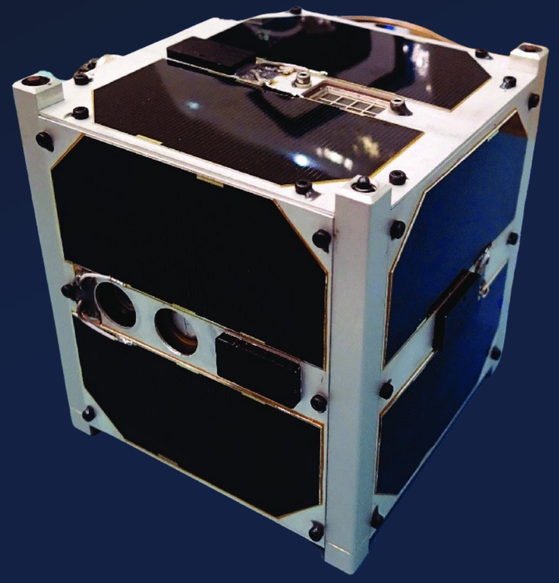
Protocols

Approach



Approach

ESTCube-1



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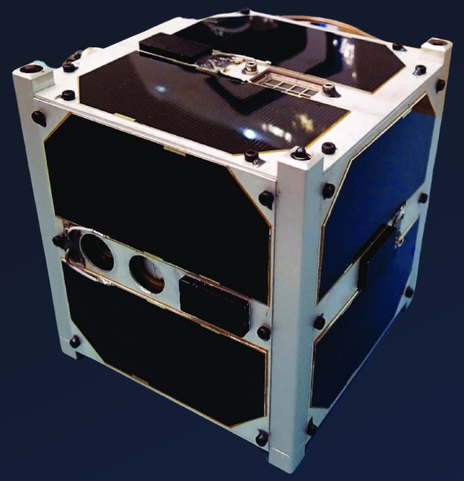
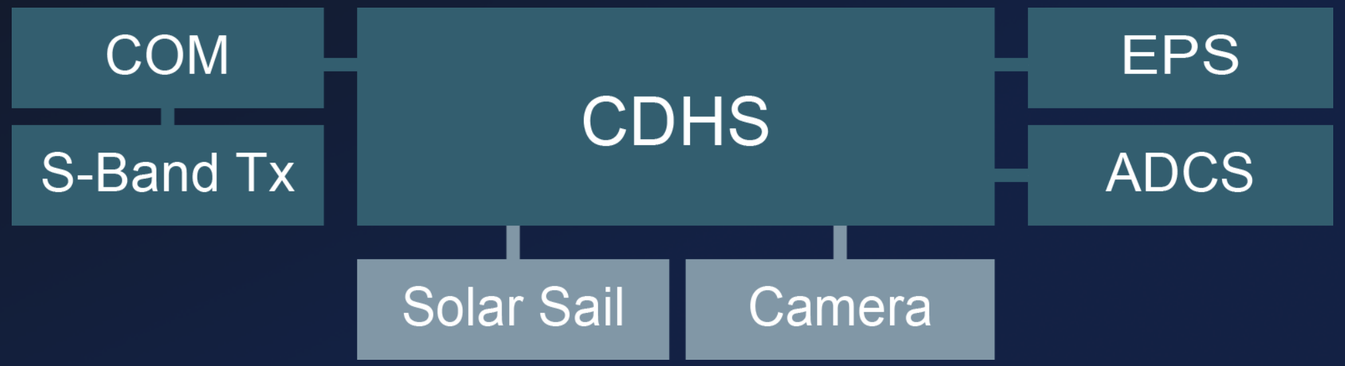


ESTCube-1

Developed by
University of Tartau



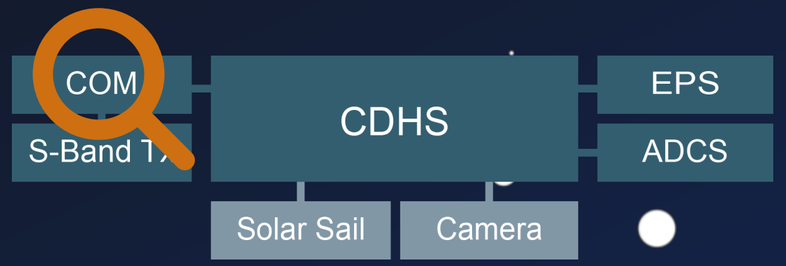
E-Sail (E. Solar Wind Sail) Propulsion

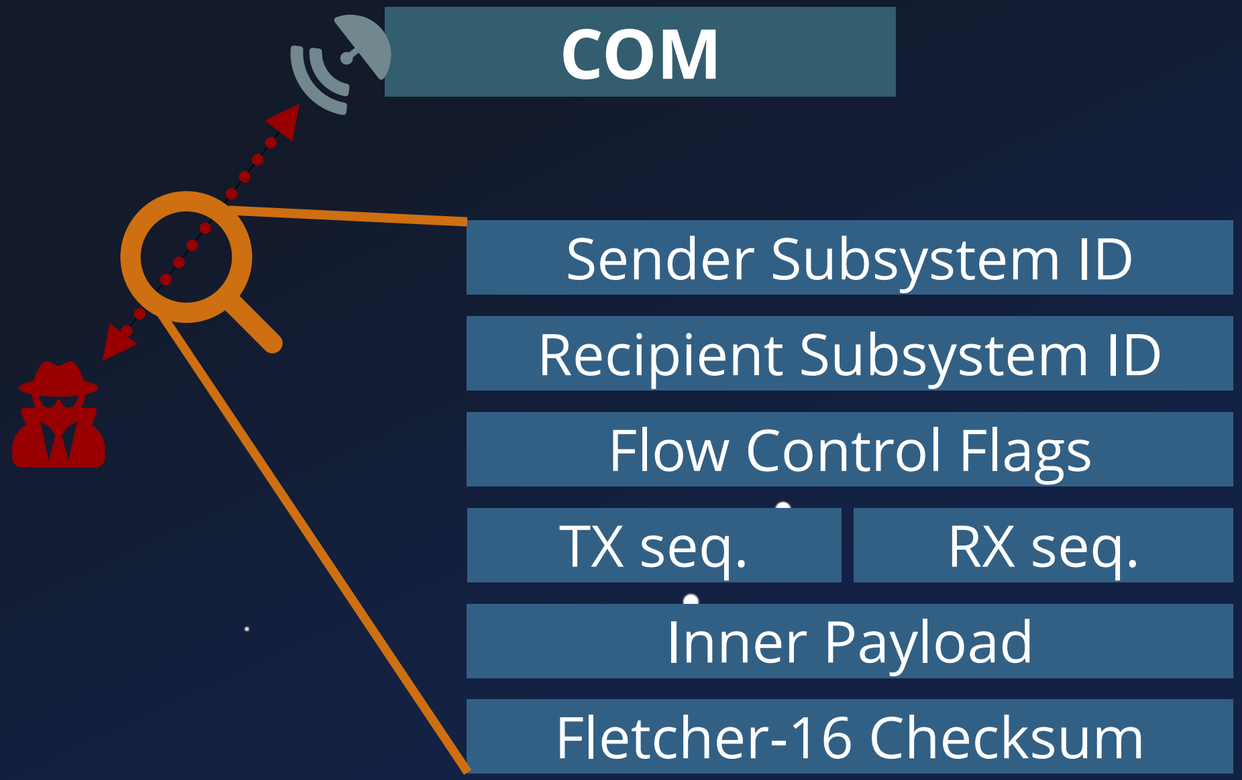
Peripherals

ARM STM32

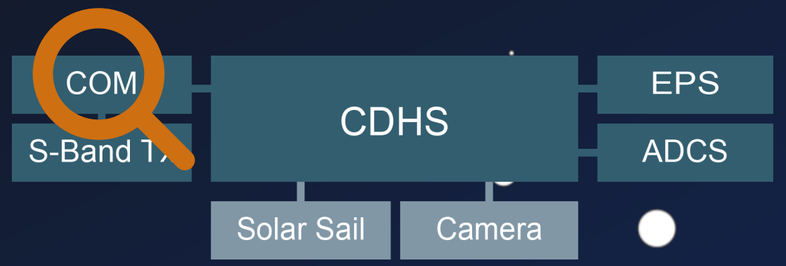
Bus Platform

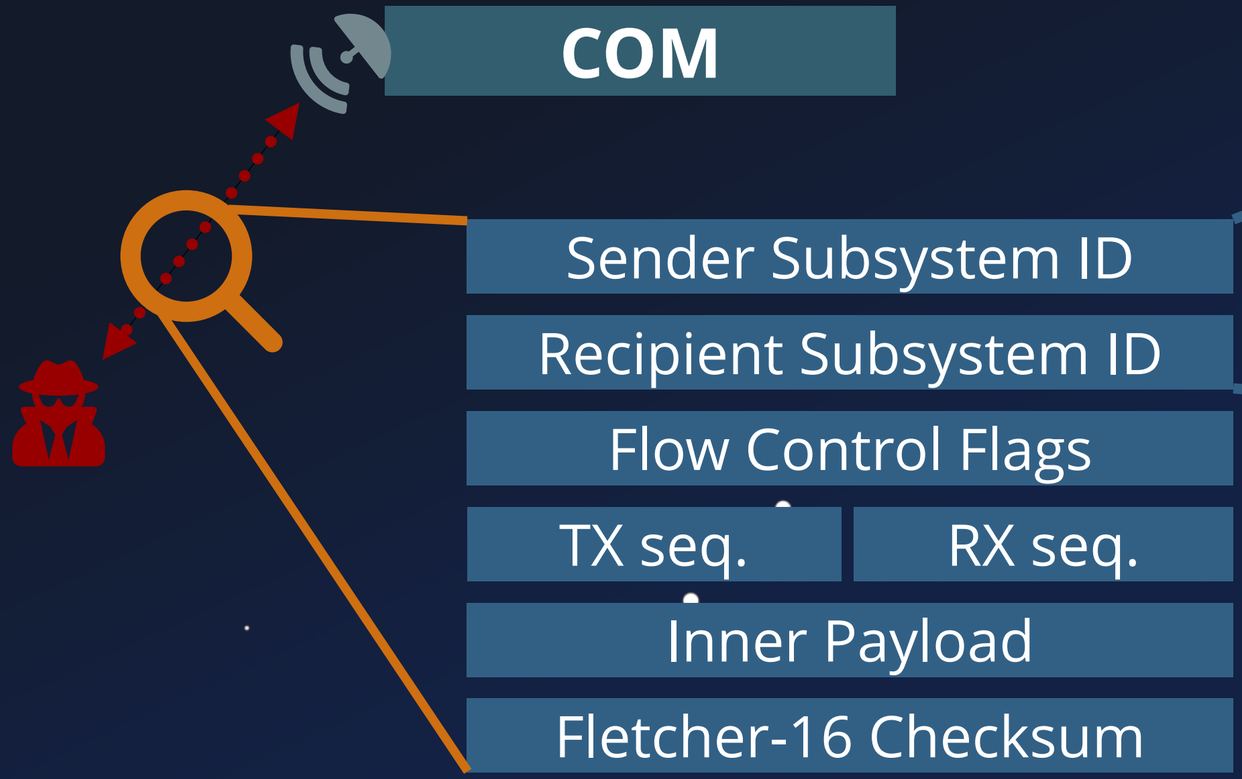
Custom Protocol





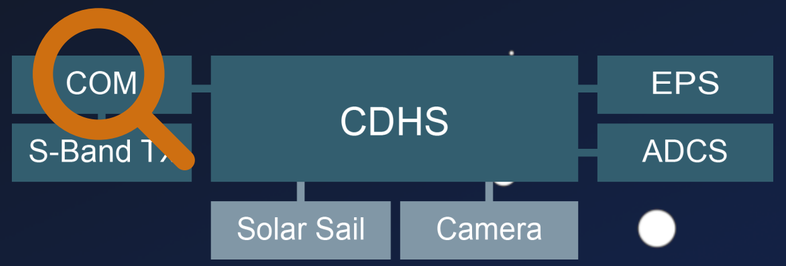
Custom Protocol





ID	Subsystem
0	EPS
1	COM
2	CDHS
...	
5	Ground Station

Custom Protocol



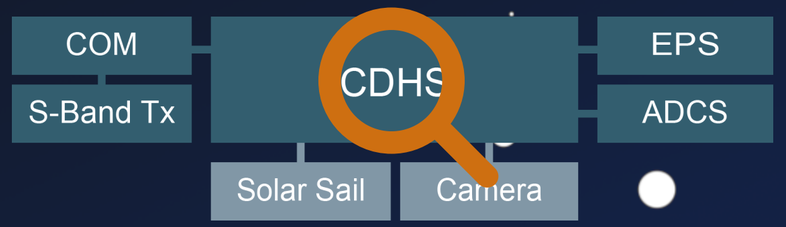
COM

- Sender Subsystem ID
- Recipient Subsystem ID
- Flow Control Flags
- TX seq. | RX seq.
- Inner Payload
- Fletcher-16 Checksum

ID	Subsystem
0	EPS
1	COM
2	CDHS
...	
5	Ground Station

	bit 0	bit 1	bit 2	bit 3	bit 4	bit 5	bit 6	bit 7
Byte 0	Command Identifier (MSB)							
Byte 1	Command Identifier (LSB)							
Byte 2	Source				Block ID			
Byte 3	Length							
...	Args							

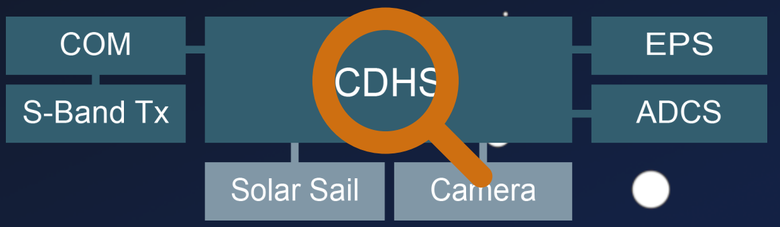
Security Analysis



COM → **CDHS**

- Bypass COM Protection
  - Missing TC Protection

Security Analysis



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int sch_handler_set_raw_memory(scheduler_cmd_t* pCmd) {
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    }
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    if (pAddr->filesystem_target) {
      // [...]
    } else {
      memcpy(pAddr->targetAddr,
             &pAddr->start_of_data_buf,
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    }
  }
  // ...
}
```

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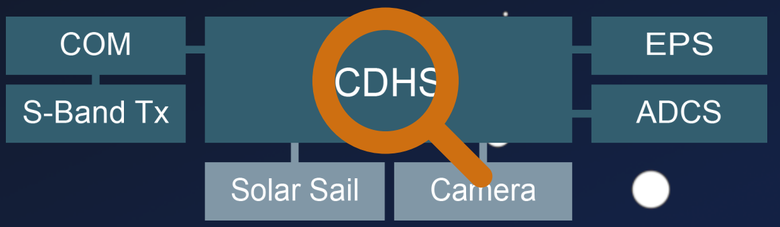

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```
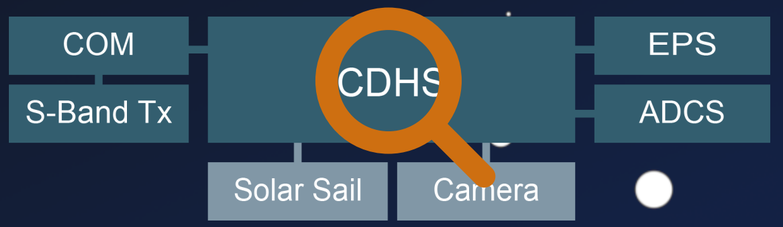
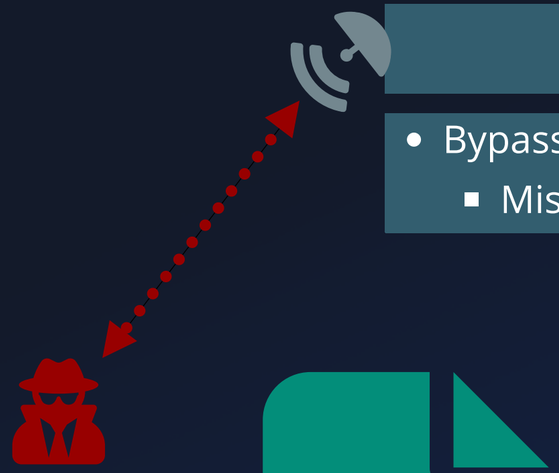

Security Analysis





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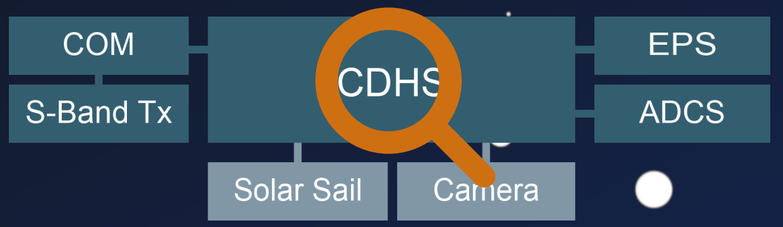
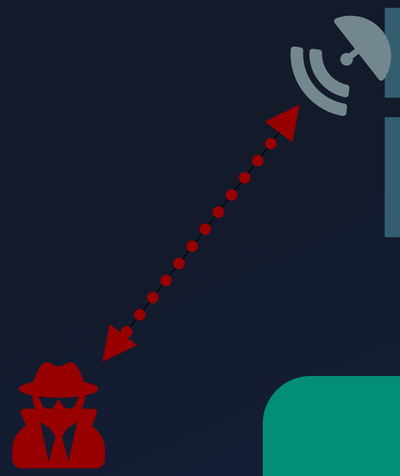
Security Analysis





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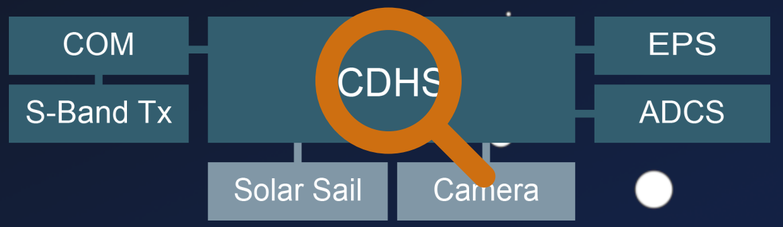
Security Analysis



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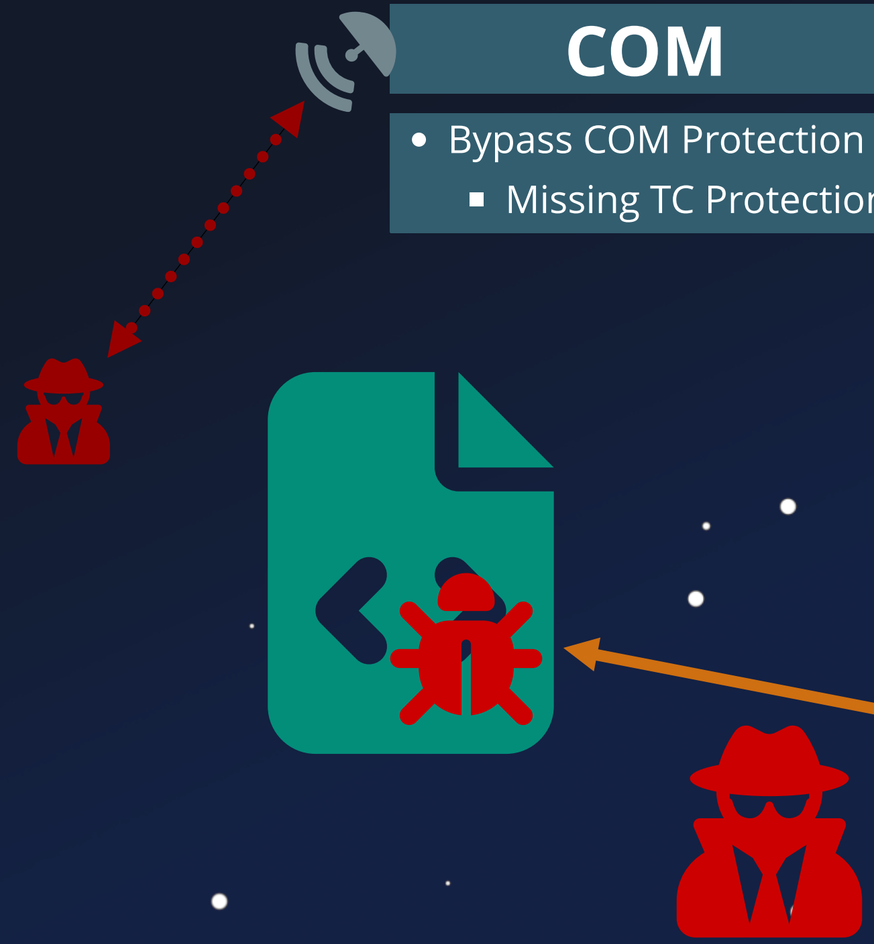

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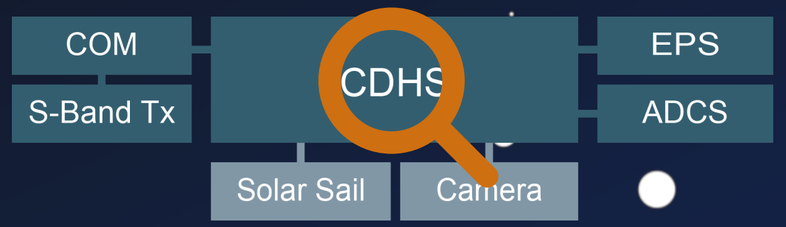
15              pAddr->writeLength);
16     }
17   }
18   // ...
19 }
```

Real-World Test



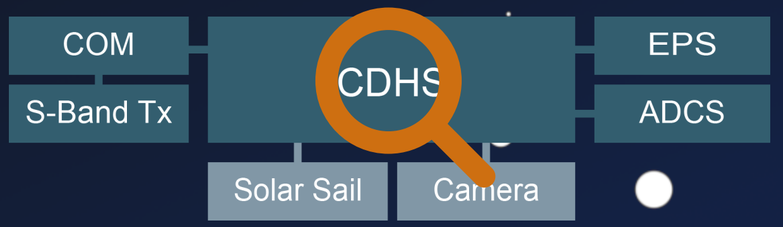
COM

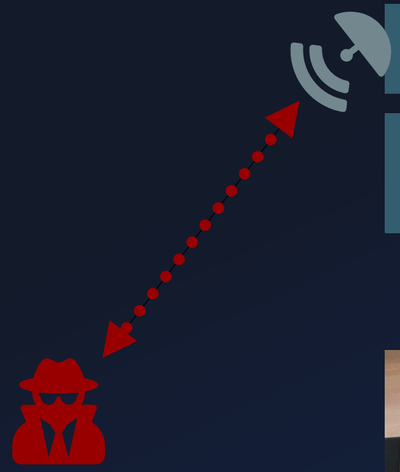
- Bypass COM Protection
  - Missing TC Protection

CDHS

- Deploy Attacker Payload
  - Dangerous TC

Real-World Test



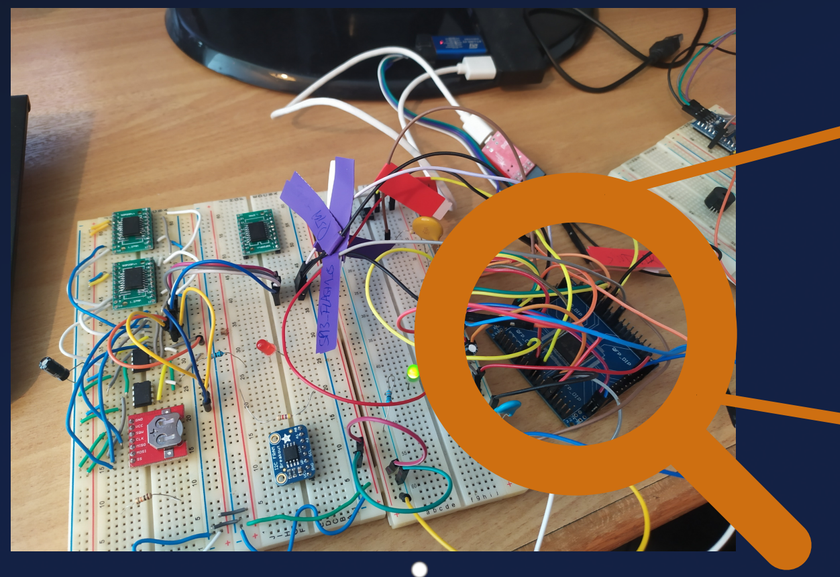


COM

- Bypass COM Protection
  - Missing TC Protection

CDHS

- Deploy Attacker Payload
  - Dangerous TC



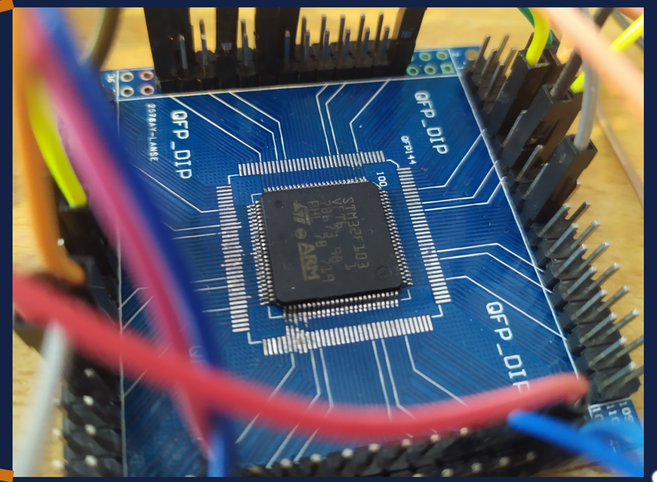
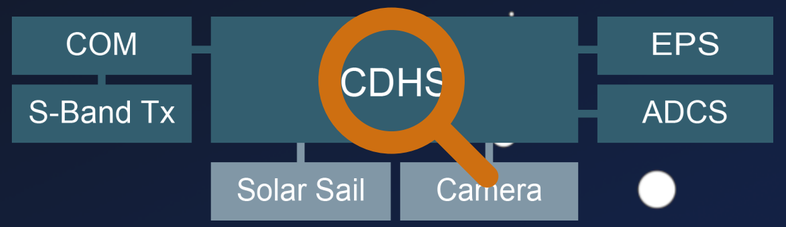


Image Source: Maximilian Gerhardt, Reverse Engineering Satellite Firmware for Security Evaluation, 13. Dec. 2021

Real-World Test



COM

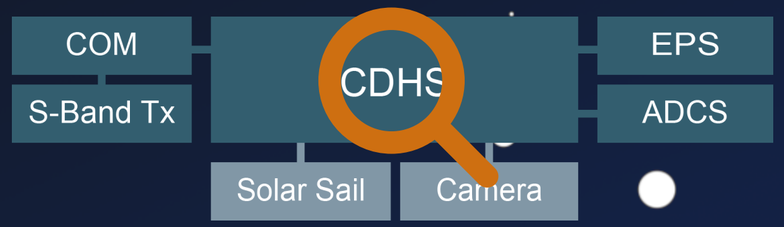
- Bypass COM Protection
  - Missing TC Protection

CDHS

- Deploy Attacker Payload
  - Dangerous TC

Bus

Real-World Test



COM

- Bypass COM Protection
  - Missing TC Protection

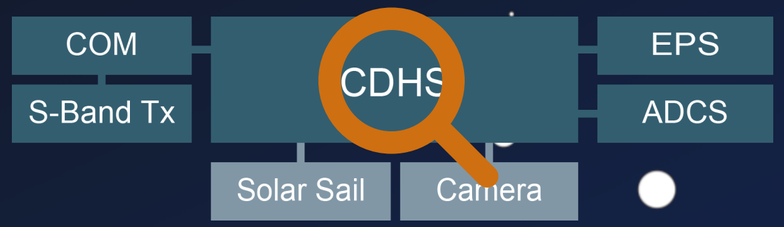
CDHS

- Deploy Attacker Payload
  - Dangerous TC

Bus

- Hijack Bus Control Flow
  - ?

Real-World Test



COM

- Bypass COM Protection
  - Missing TC Protection

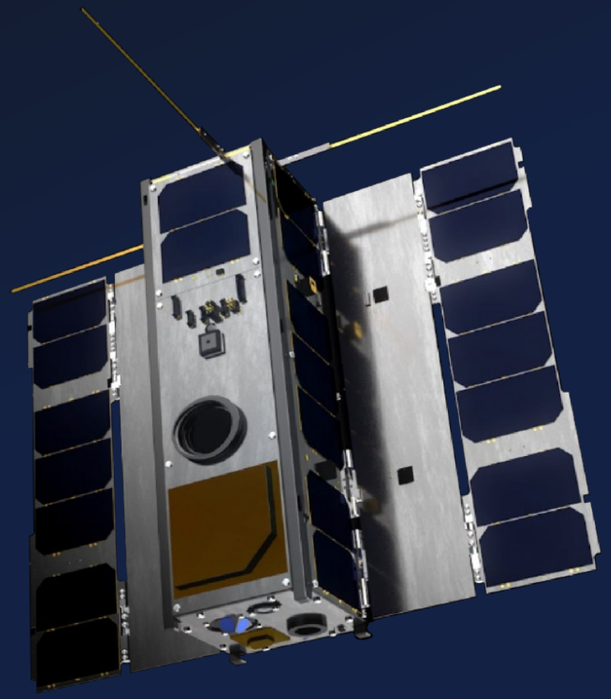
CDHS

- Deploy Attacker Payload
  - Dangerous TC

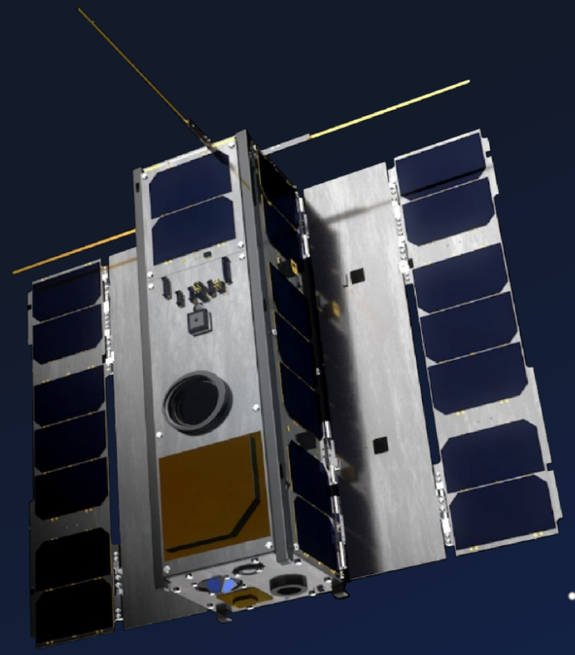
Bus

- Hijack Bus Control Flow
  - ?
- Full Bus Privileges
  - ?

OPS-Sat



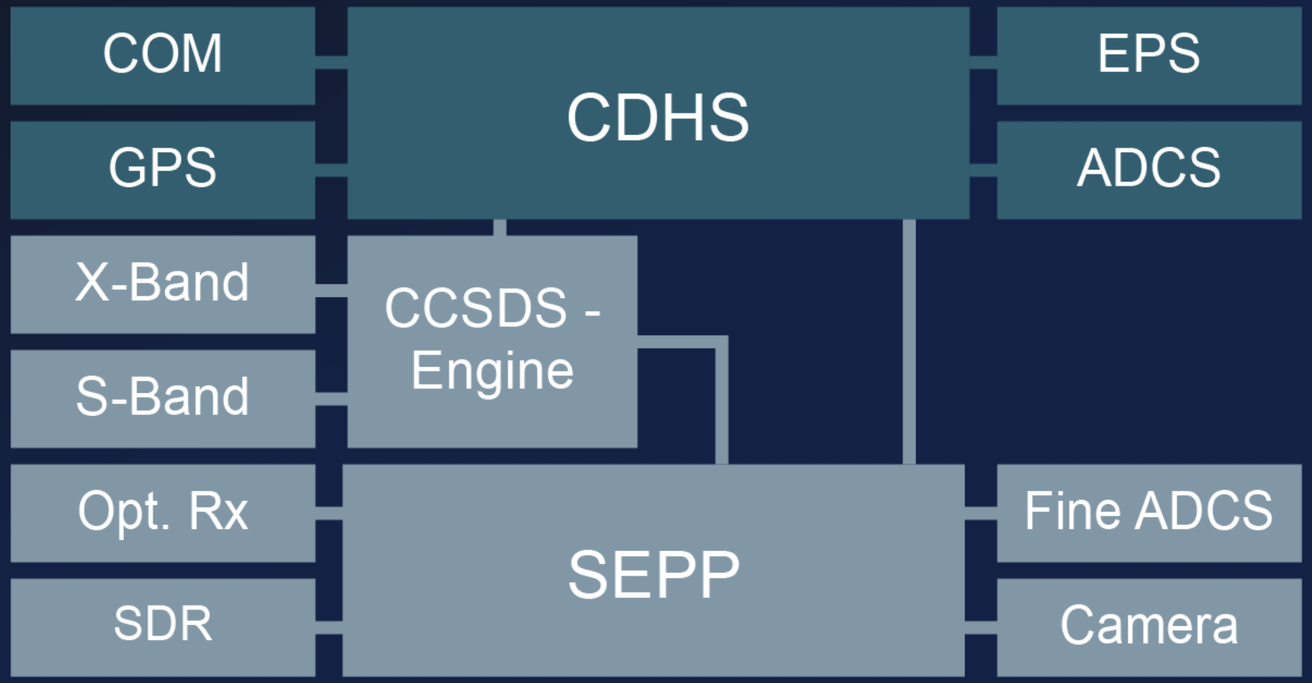
System Chart



Experimenter

Operated by ESA

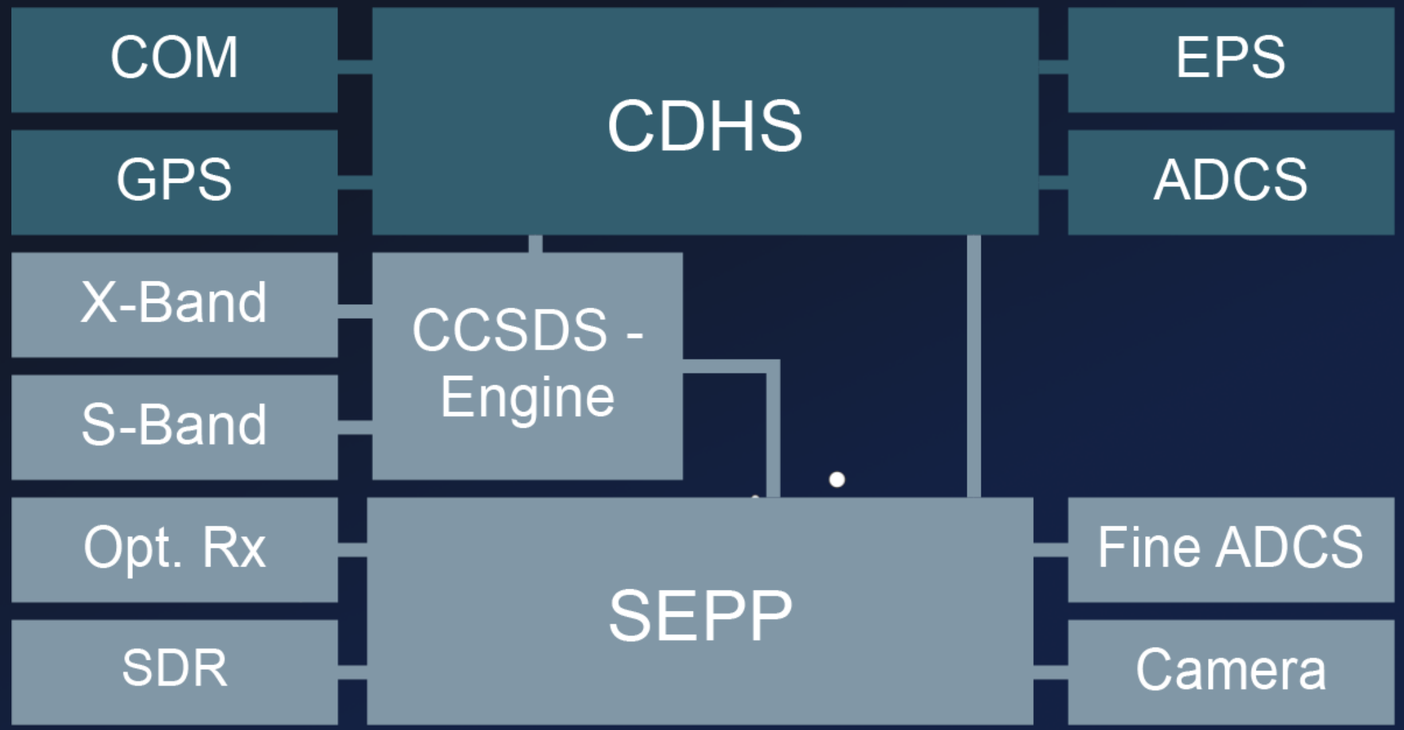
Open for Research



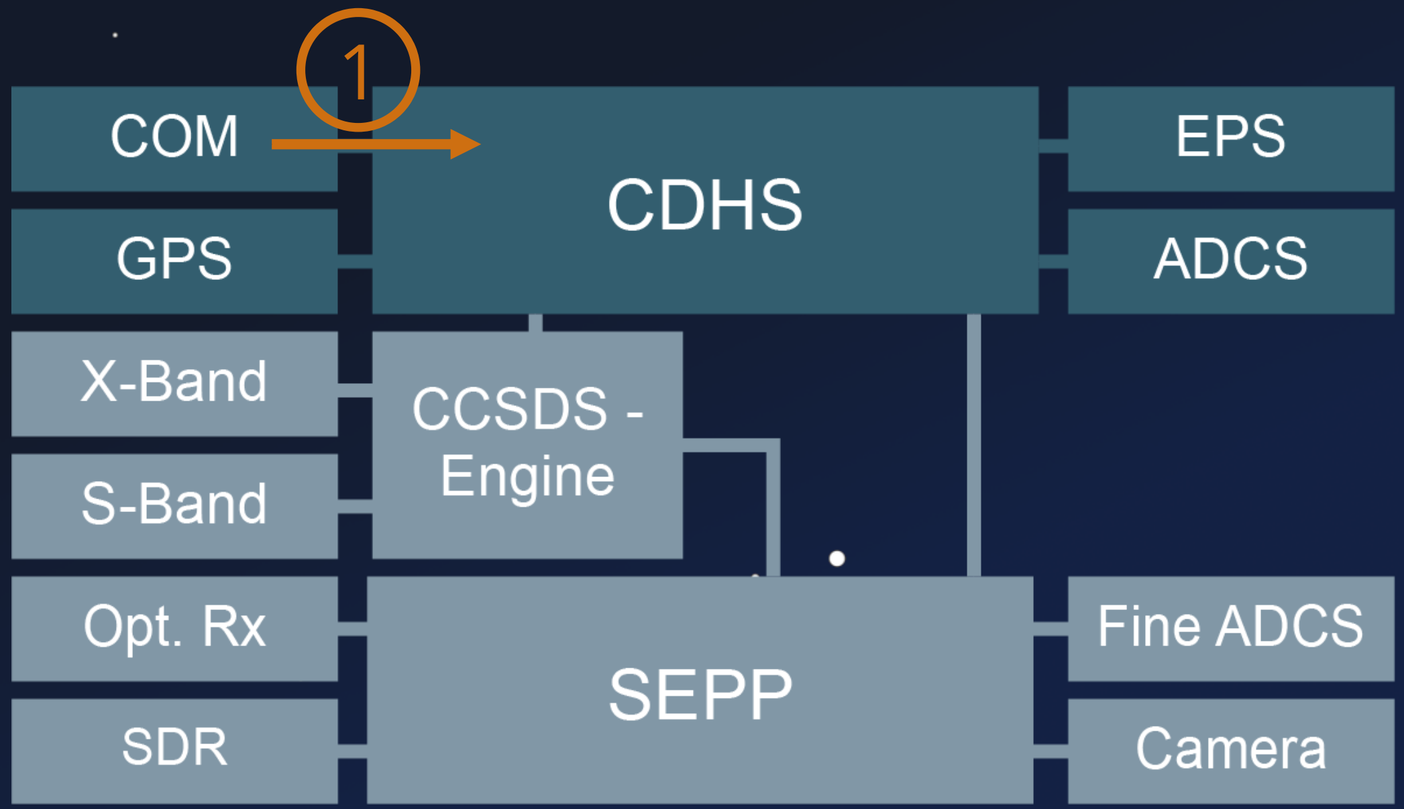
S-/X-Band, SDR, Optical Rx., Camera, ...

Peripherals

System Chart

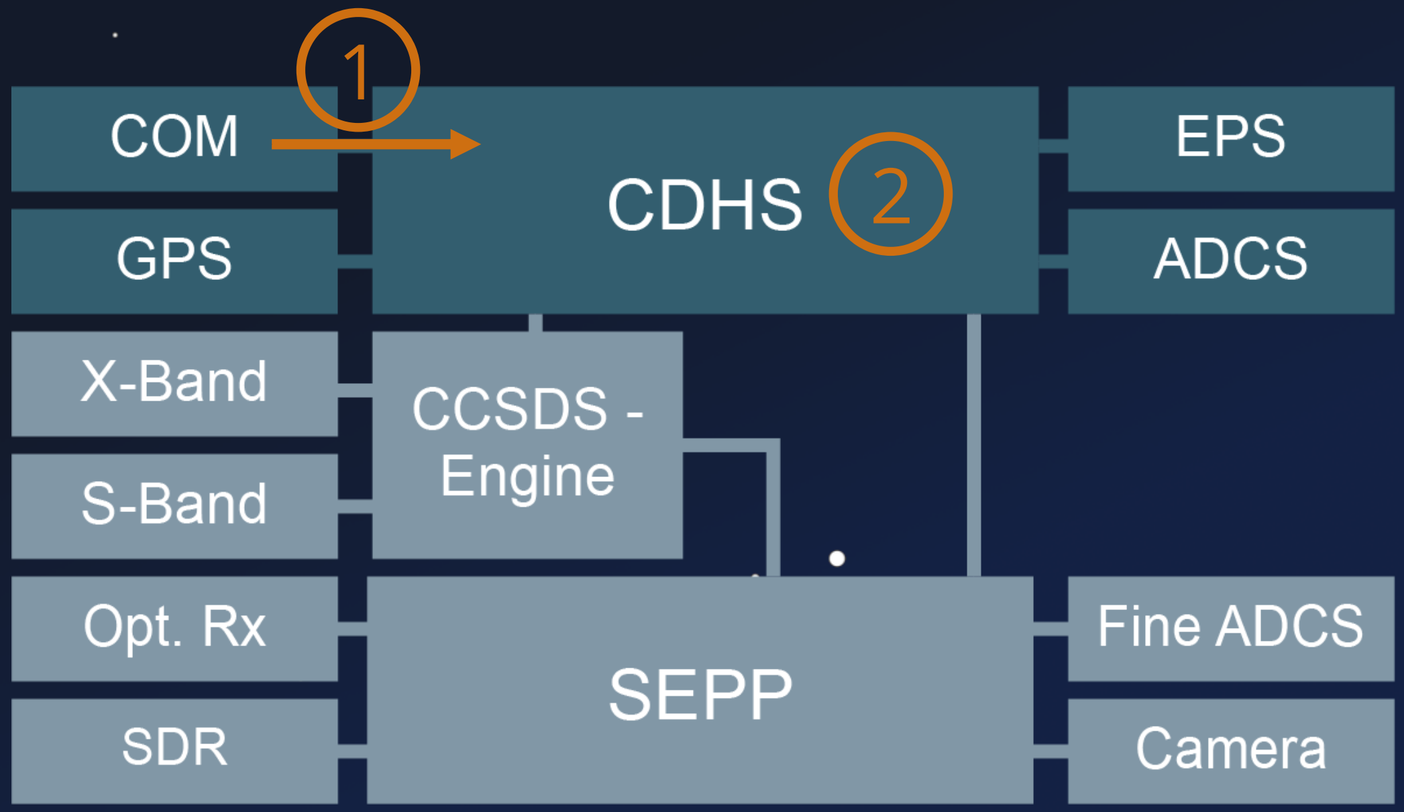


System Chart



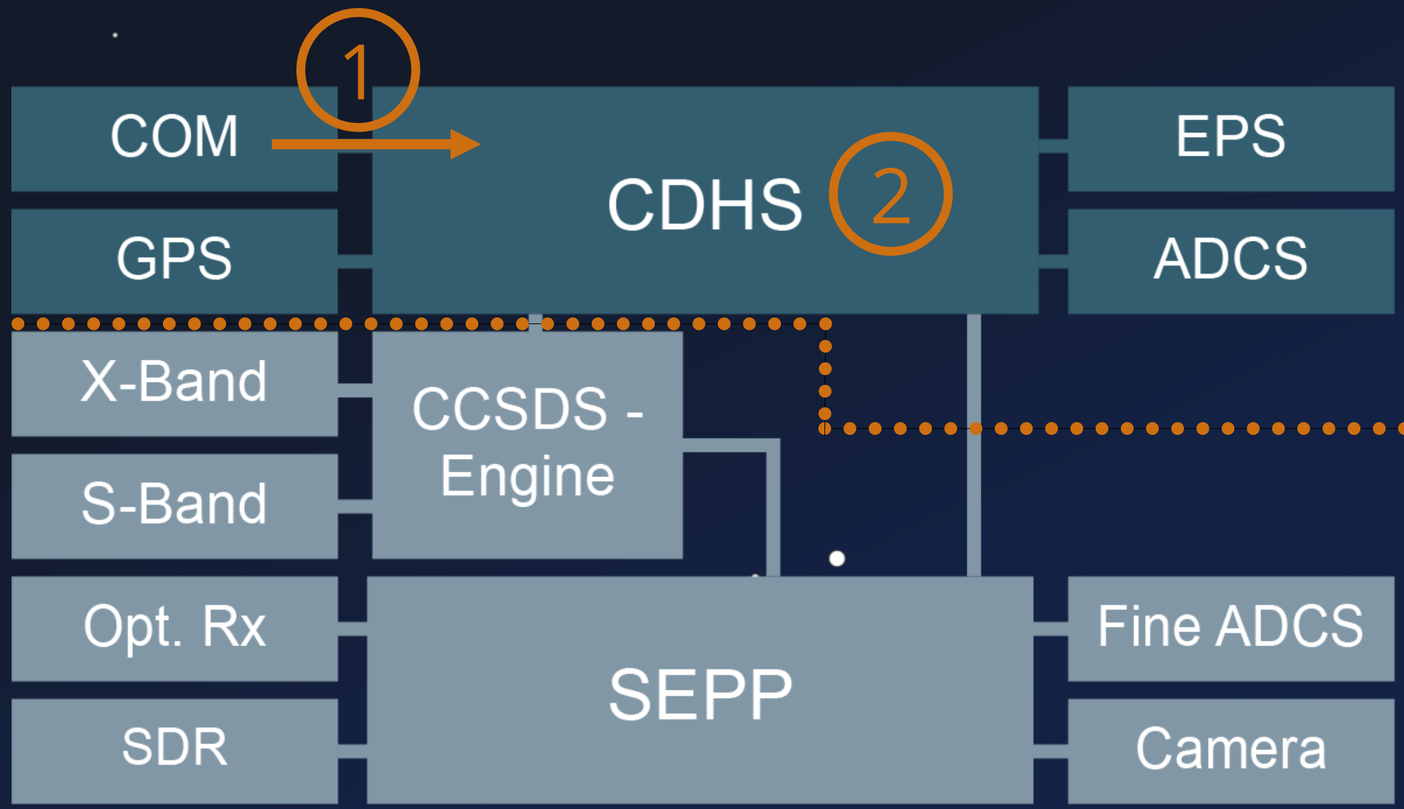
1 Cubesat Space Protocol (CSP)

System Chart



1. Cubesat Space Protocol (CSP)
2. AVR32 AT32UTC3, FreeRTOS

System Chart



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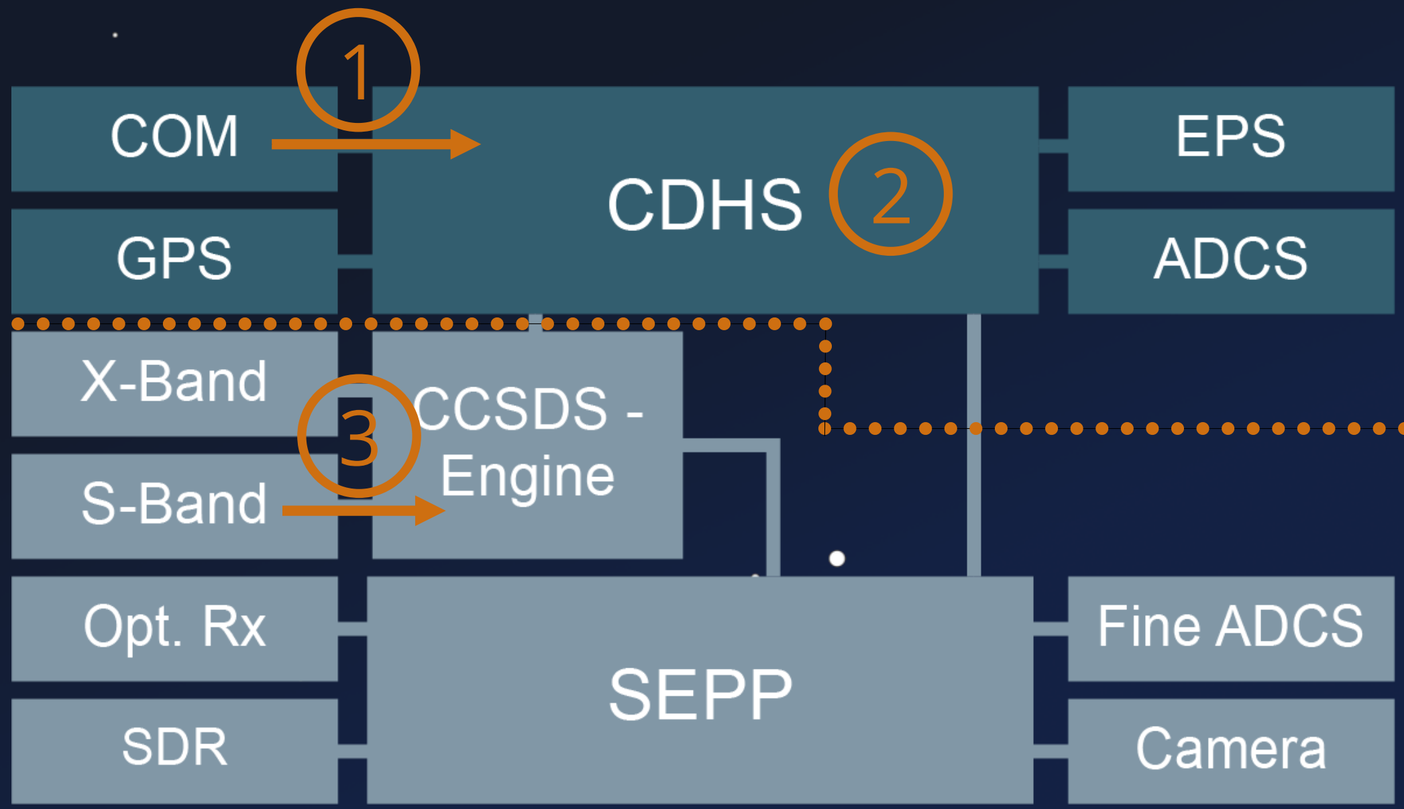
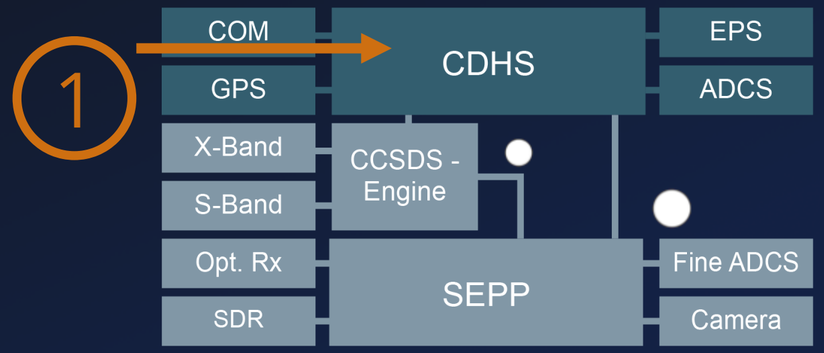


1. Cubesat Space Protocol (CSP)
2. AVR32 AT32UTC3, FreeRTOS
3. CCSDS Protocol Stack

UHF-Stack



Cubesat Space Protocol (CSP) v1

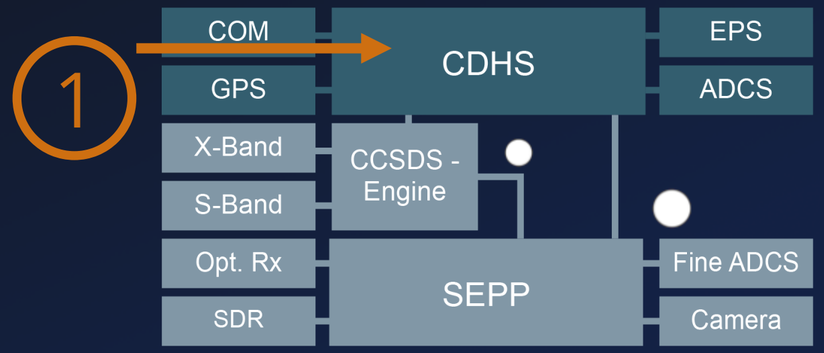
TCP/IP Oriented Design

CSP Header 1.x																													
Bit offset	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	Priority		Source					Destination					Destination Port						Source Port						Reserved				HMAC	XTEA	RDP	CRC
32	Data (0 – 65,535 bytes)																															

Source: https://en.wikipedia.org/wiki/Cubesat_Space_Protocol

/ libcsp

UHF-Stack



Cubesat Space Protocol (CSP) v1

Security Features

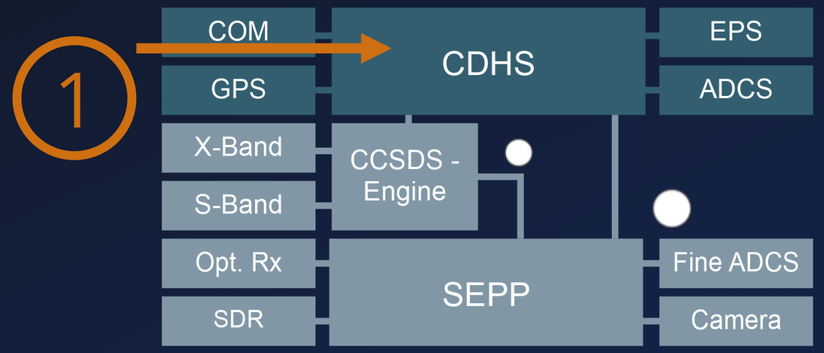
- HMAC-SHA1 Authentication
- XTEA Encryption Support

Security Issues

1. MAC comparison leaks timing data #44
   - `memcmp` to compare the digest
2. HMAC doesn't protect headers #45
   - Same problem for the CRC checks
3. XTEA encrypt packet nonce too predictable #162
   - `const uint32_t nonce = (uint32_t)rand();`

Authors: Issues fixed in libcsp v2

UHF-Stack



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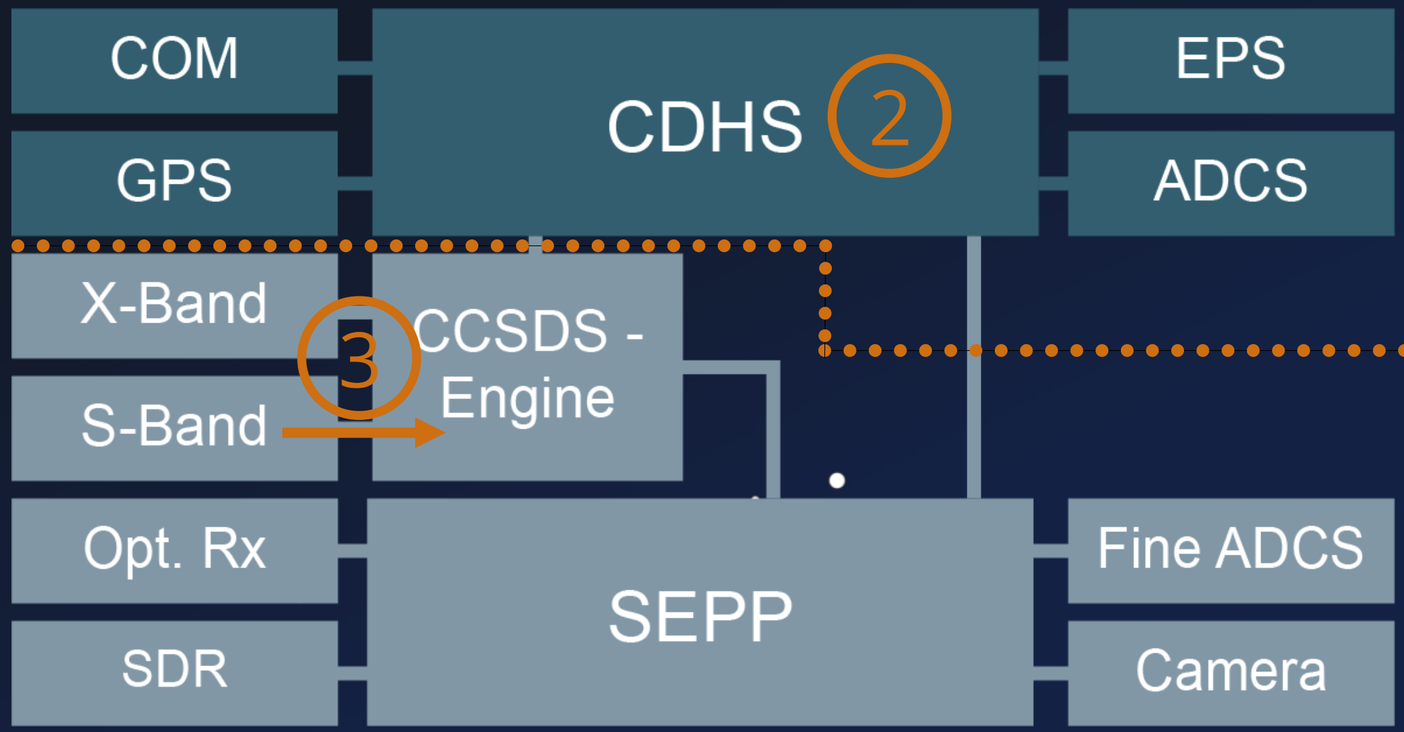
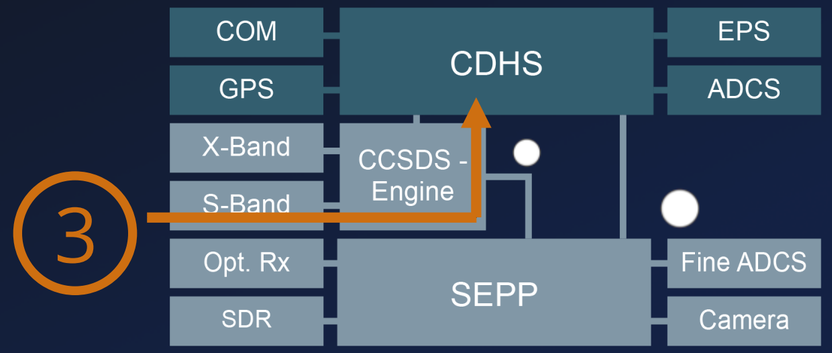


2 AVR32 AT32UTC3, FreeRTOS

3 CCSDS Protocol Stack

S-Band Stack



CCSDS - Protocol Stack

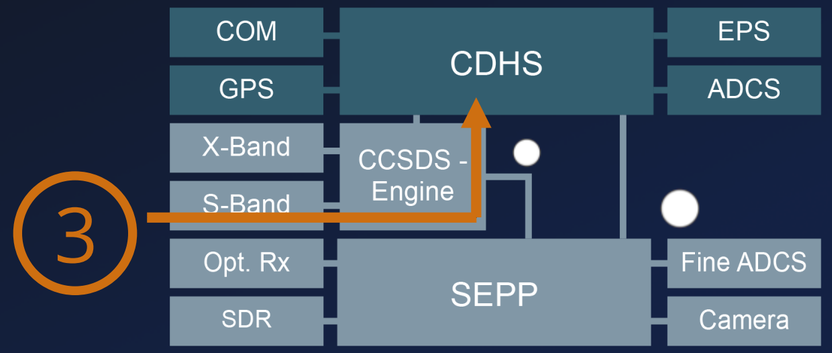
Message Abstraction | ... | IPSec

Space Packet Protocol | IP

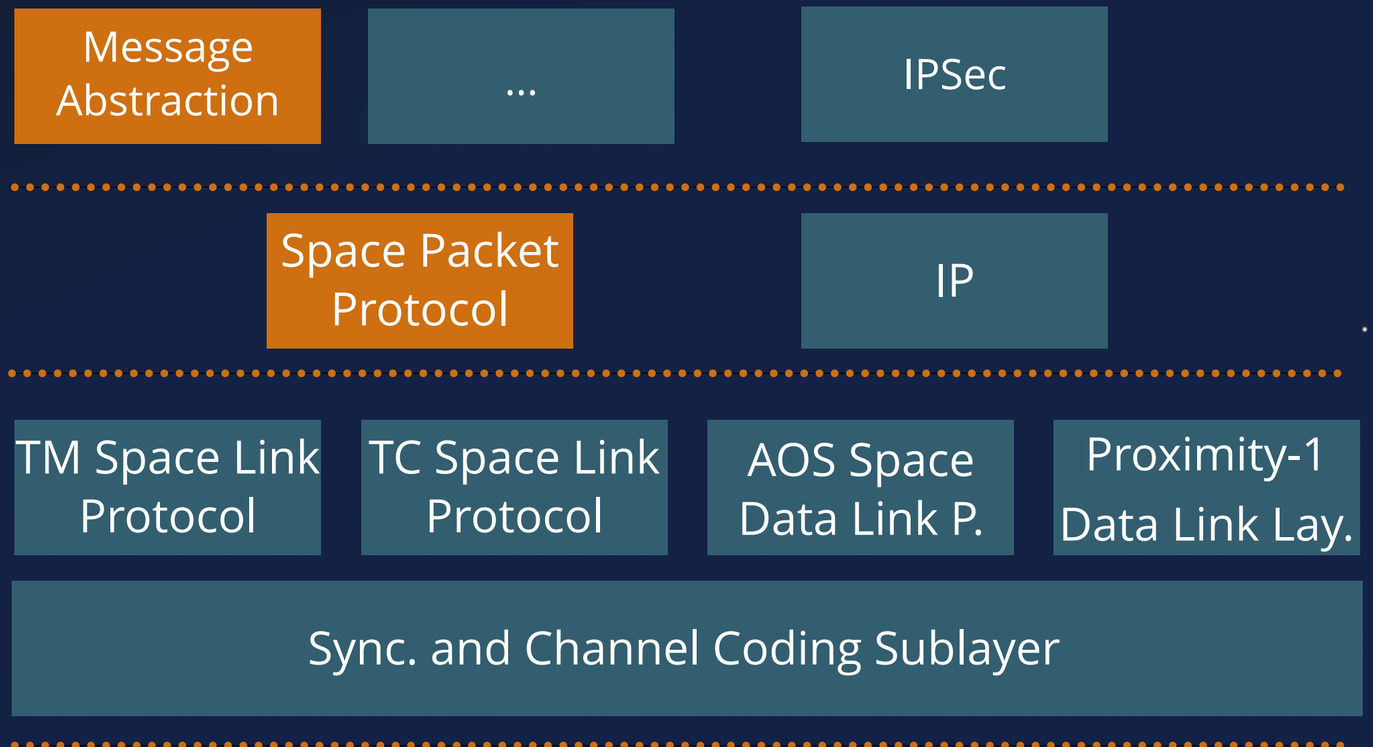
TM Space Link Protocol | TC Space Link Protocol | AOS Space Data Link P. | Proximity-1 Data Link Lay.

Sync. and Channel Coding Sublayer

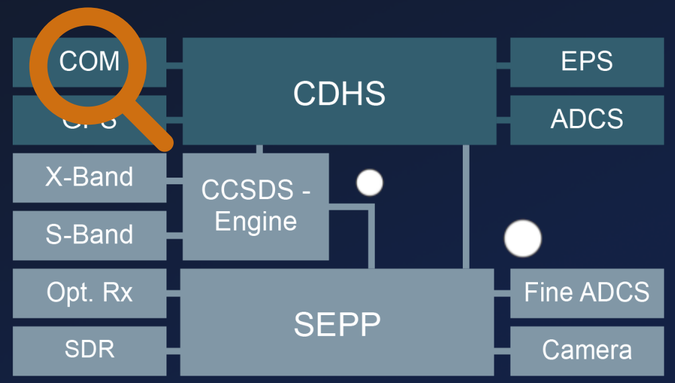
S-Band Stack



CCSDS - Protocol Stack



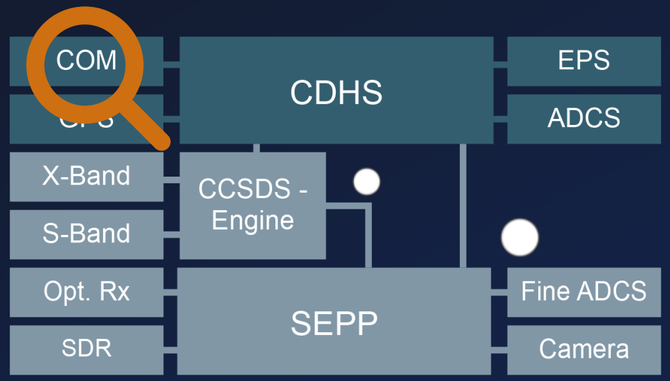
Unprotected TCs



Unprotected TCs

COM

```
1  int csp_route_security_chek(...) {
2    if (packet->id.flags & CSP_FXTEA) {
3      csp_log_error("Received XTEA encrypted packet, but CSP
   was compiled without XTEA support. Discarding packet");
4    }
5
6    // ...
7
8    if (packet->id.flags & CSP_FHMAC) {
9      csp_log_error("Received packet with HMAC, but CSP was
   compiled without HMAC support. Discarding packet");
10   }
11
12    // ...
13 }
```



Unprotected TCs

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8      }
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11       // [...]
12     } else {
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12     } else {
13       memcpy(pAddr->targetAddr,
14              &pAddr->start_of_data_buf,
15              pAddr->writeLength);
16     }
17   }
18   // ...
19 }
```
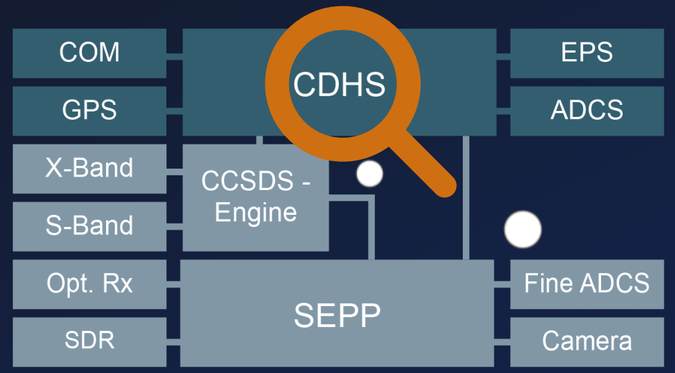

Vulnerable TC

Cubesat Space Protocol (CSP) → ADCS Server




```c
void task_adcs_servr() {
  char log_file_name [32];

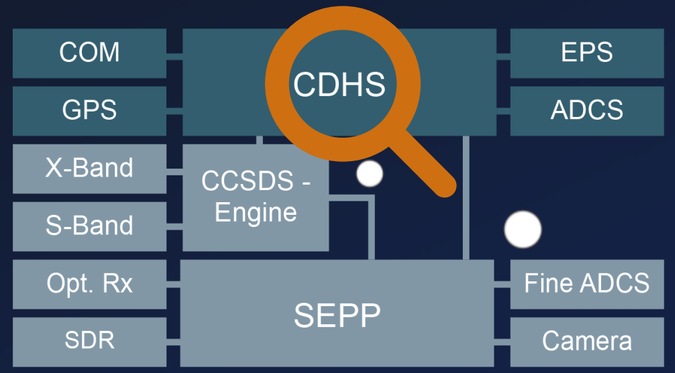
  csp_listen(socket, 10);
  csp_bind(socket, port);

  do {
    do {
      conn = csp_accept(socket, 0xff);
    } while (do_wait_for_conn);

    packet = csp_read(conn, 10);
    if (packet) {
      packet_data = packet->data;
      switch(*packet_data) {
        // [...]
        case SET_LOGFILE: {
          packet_data = packet->data + 0xf;
          log_file_name[0] = '\0';
          strcat(log_file_name,packet_data);
          // ...
        }
      }
    }
  }
```

Vulnerable TC

Cubesat Space Protocol (CSP) → ADCS Server

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          // ...
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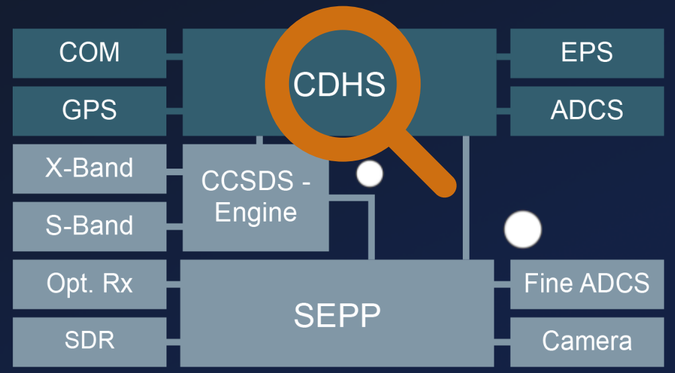
      }
    }
  }
```

Vulnerable TC

Cubesat Space Protocol (CSP) → ADCS Server



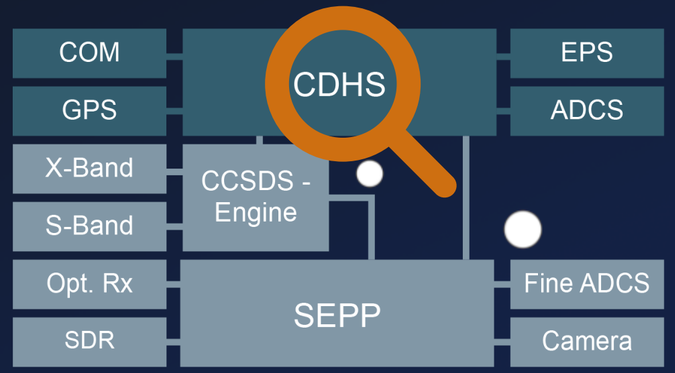

```c
void task_adcs_servr() {
  char log_file_name [32];

  csp_listen(socket, 10);
  csp_bind(socket, port);

  do {
    do {
      conn = csp_accept(socket, 0xff);
    } while (do_wait_for_conn);

    packet = csp_read(conn, 10);
    if (packet) {
      packet_data = packet->data;
      switch(*packet_data) {
        // [...]
        case SET_LOGFILE: {
          packet_data = packet->data + 0xf;
          log_file_name[0] = '\0';
          strcat(log_file_name,packet_data);
          // ...
        }
      }
    }
  }
```

Defenses - 404?



COM

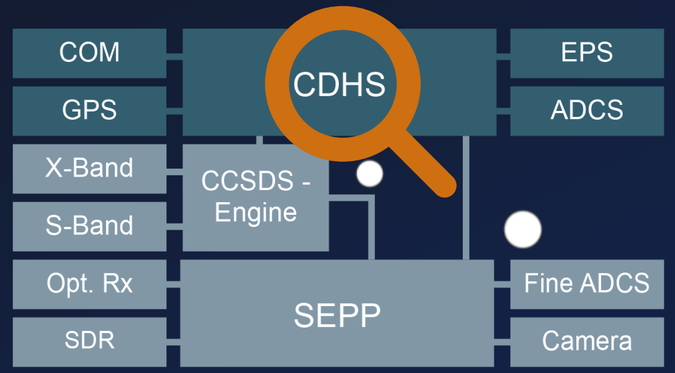
- Bypass COM Protection
  - Missing TC Protection

CDHS

- Deploy Attacker Payload
  - Vulnerable TC

Bus

Defenses - 404?



COM

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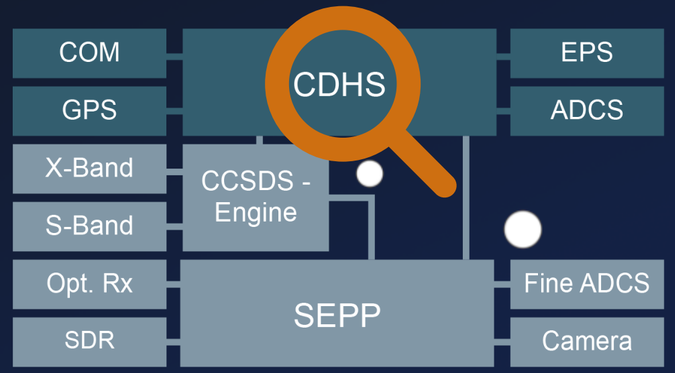
- Deploy Attacker Payload
  - Vulnerable TC

Bus

- Hijack Bus Control Flow

Defenses - 404?



COM

- Bypass COM Protection
  - Missing TC Protection

CDHS

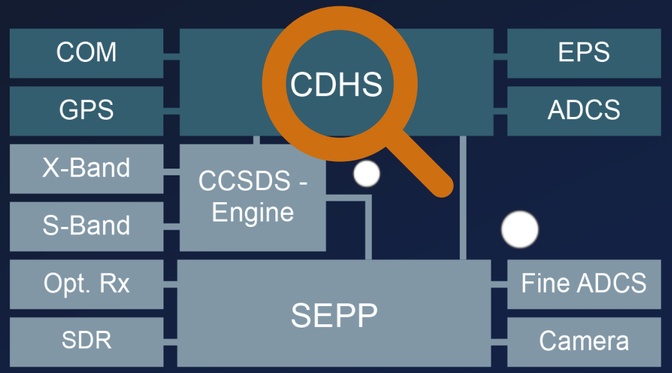
- Deploy Attacker Payload
  - Vulnerable TC

Bus

- Hijack Bus Control Flow

- No OS-Defenses
  - ASLR
  - NX Stack

Defenses - 404?



COM

- Bypass COM Protection
  - Missing TC Protection

→

CDHS

- Deploy Attacker Payload
  - Vulnerable TC

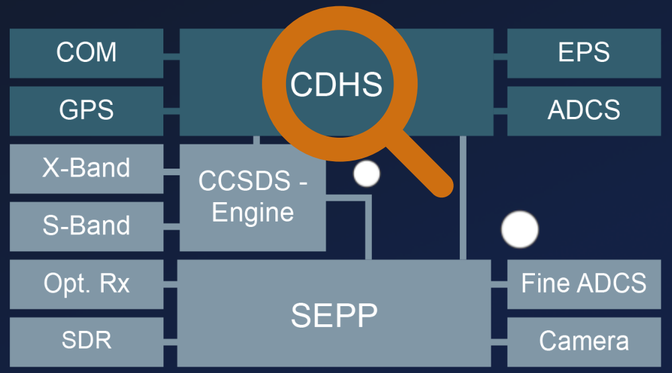
→

Bus

- Hijack Bus Control Flow

- No OS-Defenses
  - ASLR
  - NX Stack
- No SW-Defenses
  - Stack Cookies

Defenses - 404?



COM

- Bypass COM Protection
  - Missing TC Protection

→

CDHS

- Deploy Attacker Payload
  - Vulnerable TC

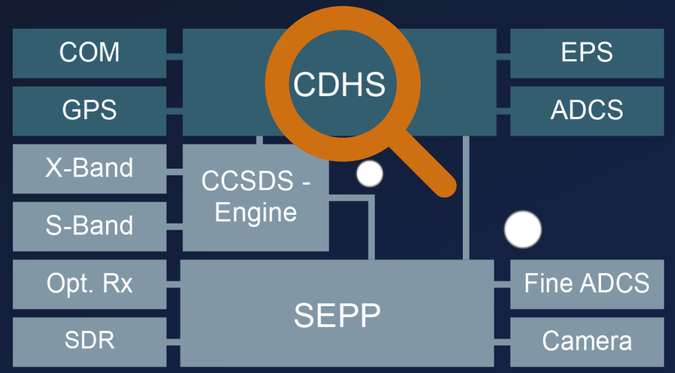
→

Bus

- Hijack Bus Control Flow
- Full Bus Privileges

- No OS-Defenses
  - ASLR
  - NX Stack
- No SW-Defenses
  - Stack Cookies

Defenses - 404?



COM

- Bypass COM Protection
  - Missing TC Protection

CDHS

- Deploy Attacker Payload
  - Vulnerable TC

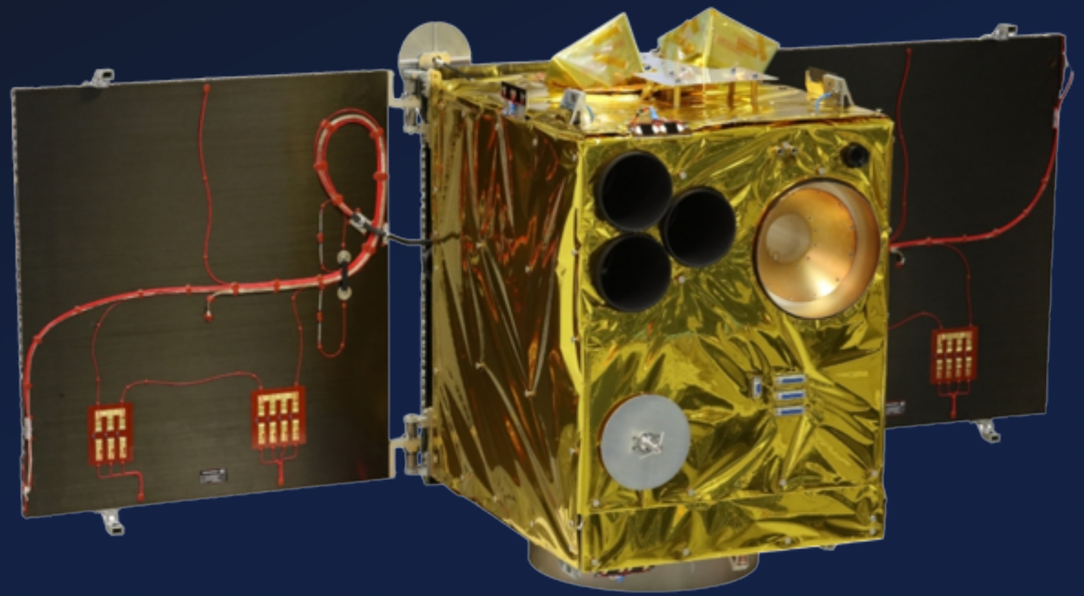
Bus

- Hijack Bus Control Flow
- Full Bus Privileges

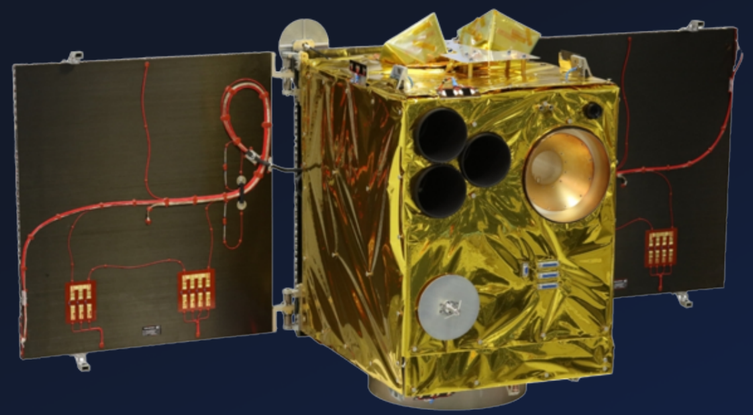
- No OS-Defenses
  - ASLR
  - NX Stack
- No SW-Defenses
  - Stack Cookies

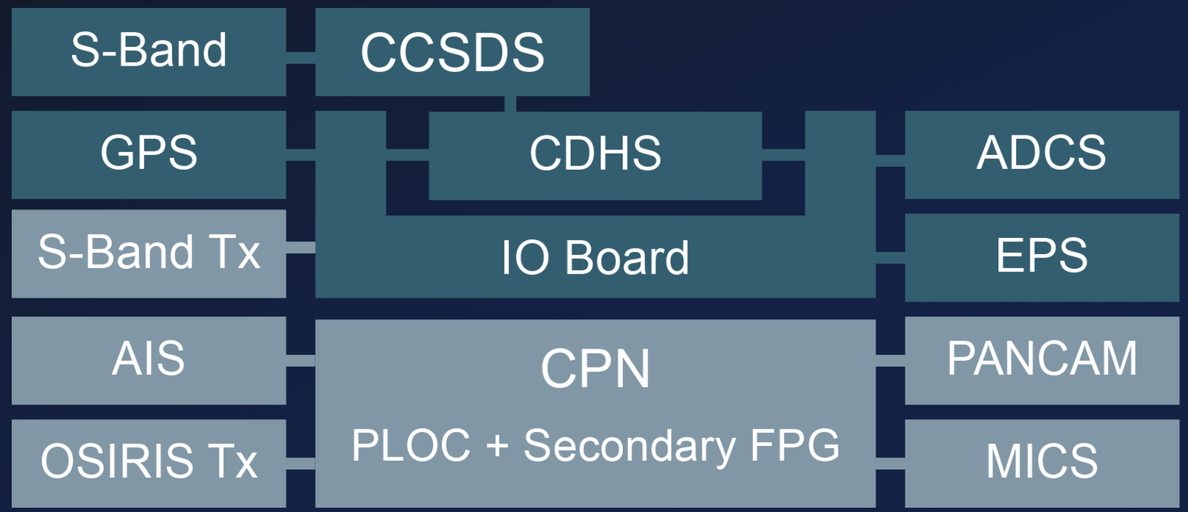
- Privilege-free RTOS

Flying Laptop



Flying Laptop





Technology Tester

Co-Developed by
Airbus Space & Defense

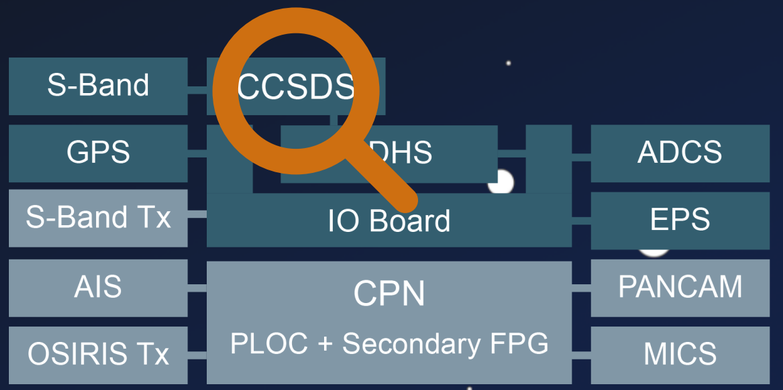
De-orbit mechanism, AIS, Camera, etc...

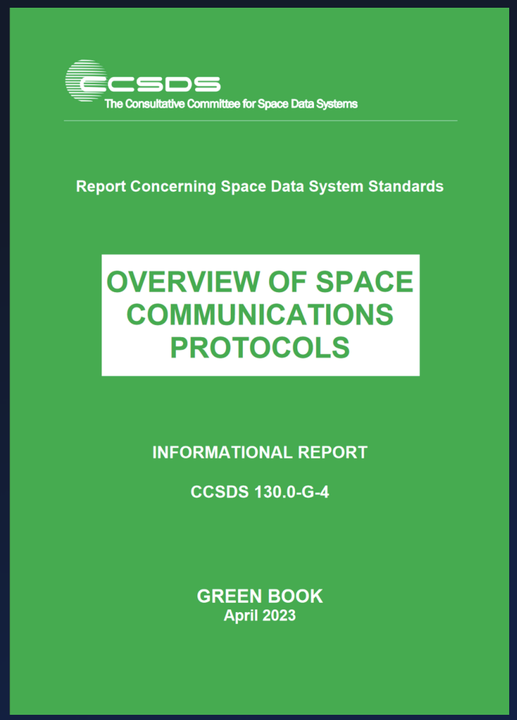
Peripherals

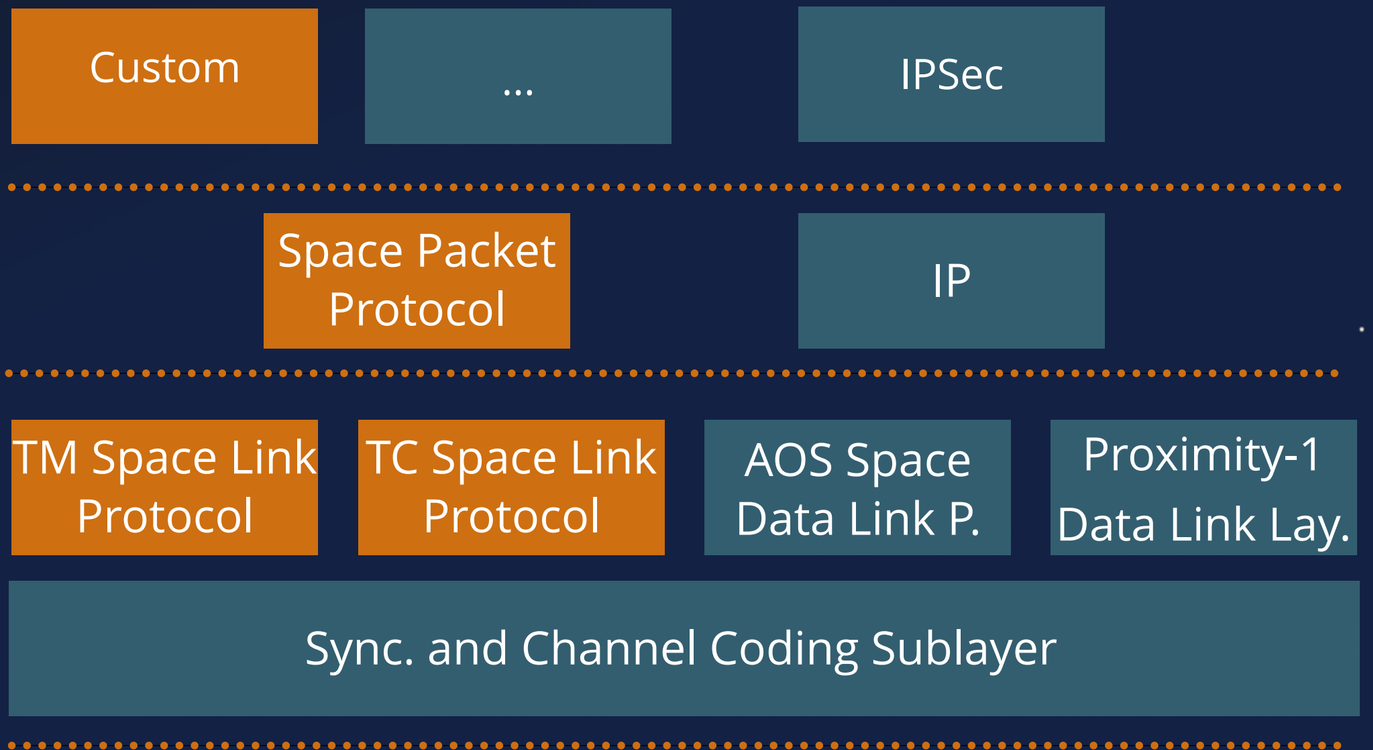
SPARC LEON 3 - OBC from Airbus S&D

Bus Platform

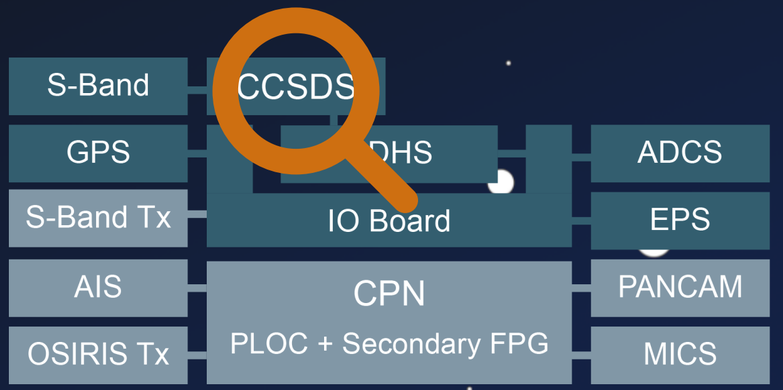
CCSDS


S-Band
CCSDS
GPS
DHS
ADCS
S-Band Tx
IO Board
EPS
AIS
CPN
PANCAM
PLOC + Secondary FPG
OSIRIS Tx
MICS


CCSDS
The Consultative Committee for Space Data Systems
Report Concerning Space Data System Standards
OVERVIEW OF SPACE COMMUNICATIONS PROTOCOLS
INFORMATIONAL REPORT
CCSDS 130.0-G-4
GREEN BOOK
April 2023


Custom
...
IPSec
Space Packet Protocol
IP
TM Space Link Protocol
TC Space Link Protocol
AOS Space Data Link P.
Proximity-1 Data Link Lay.
Sync. and Channel Coding Sublayer

CCSDS


S-Band
GPS
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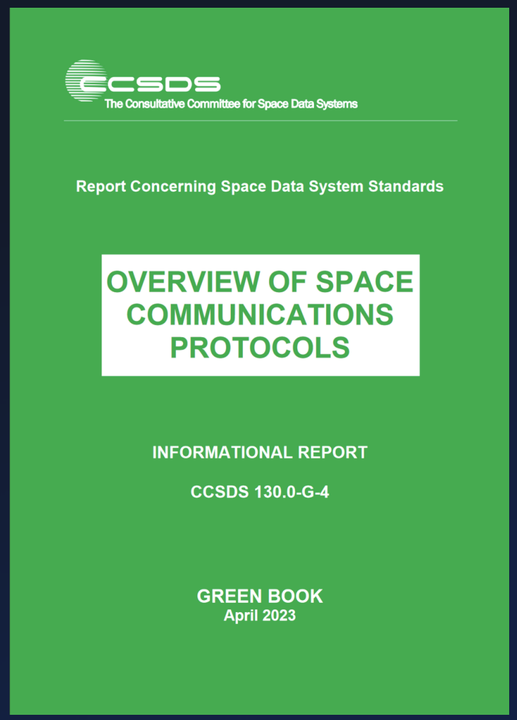
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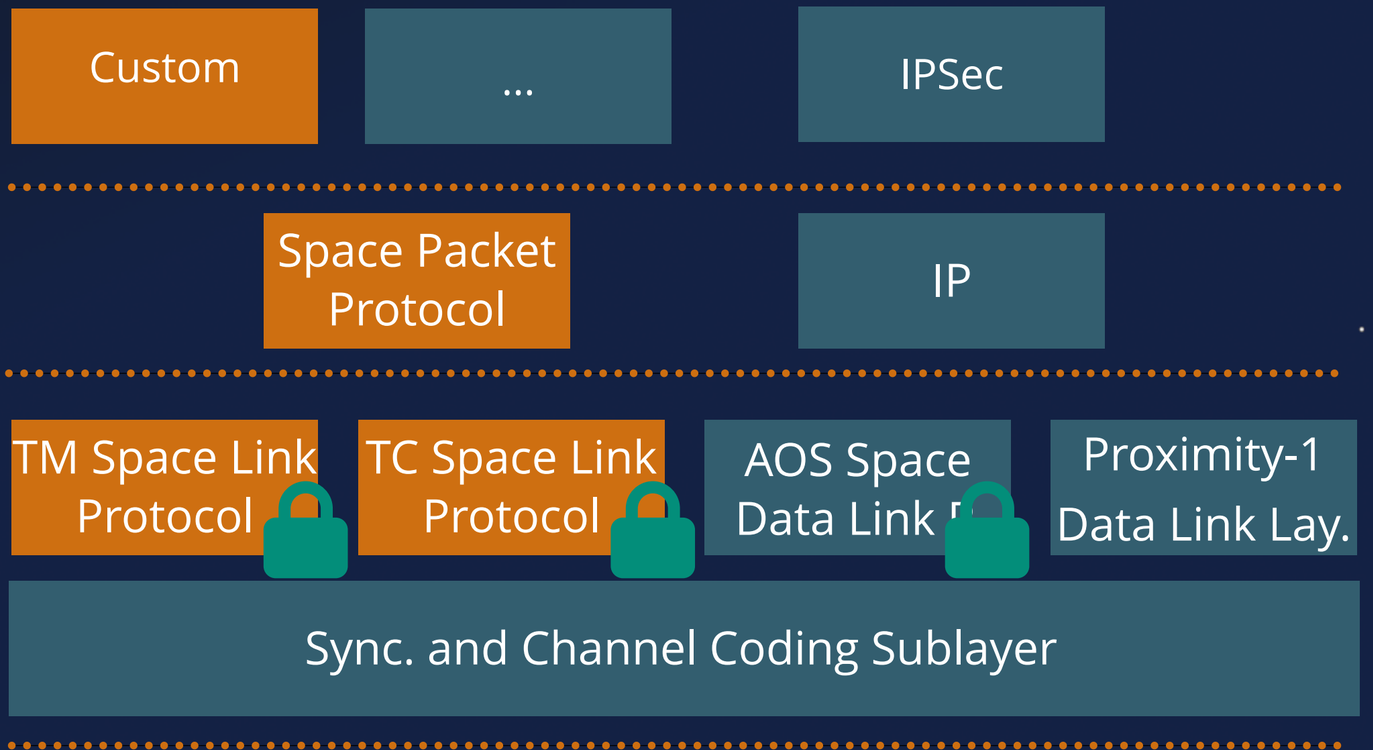
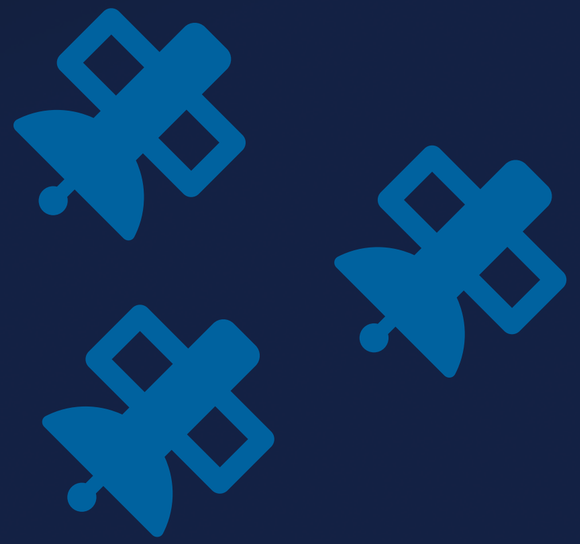

Custom
...
IPSec
Space Packet Protocol
IP
TM Space Link Protocol
TC Space Link Protocol
AOS Space Data Link
Proximity-1 Data Link Lay.
Sync. and Channel Coding Sublayer

Bigger Picture

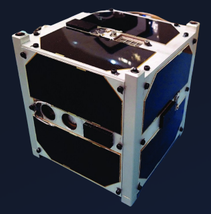
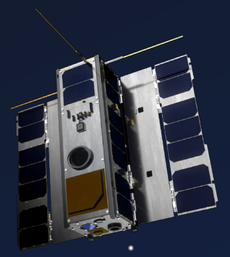
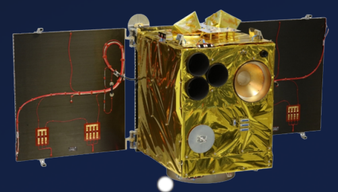
“ But it's different for […] satellites.

“ But it's different for […] satellites, …. right?

Developer Survey



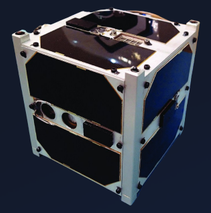
TC Protocols

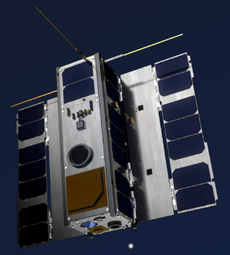
	Custom	Standard	Weight
	✓	✗	~ 1.3 kg
	~	✓	~ 5.4 kg
	✗	✓	~ 120 kg

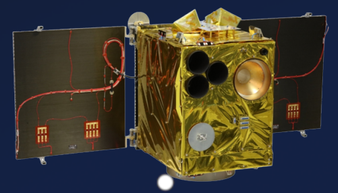
Weight ≈ Money

TC Protocols

Custom / Standard





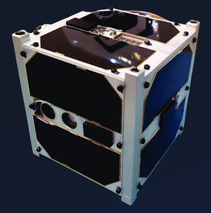


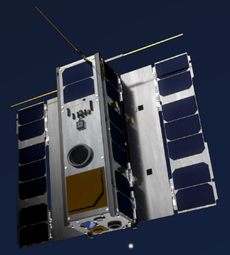
	1-50 kg	50-100 kg	> 100 kg
Standard	1	1	**4**
Custom	**6**	1	0
Abstains	3	0	1
∑	10	2	5

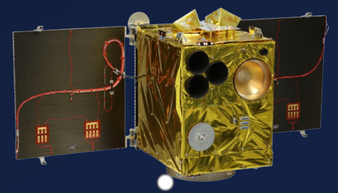
Weight ≈ Money

TC Protocols

Custom /
Standard







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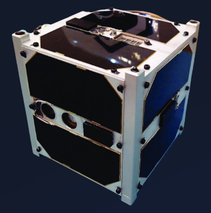

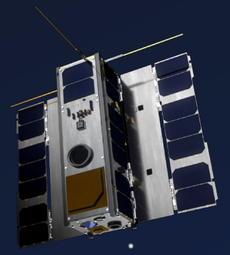

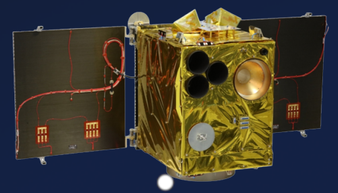

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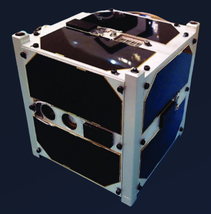
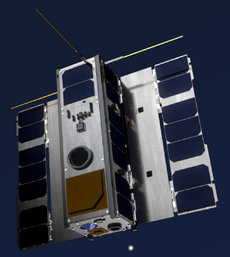
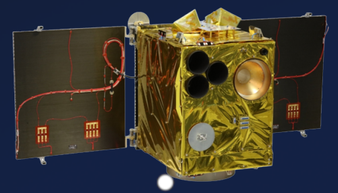
TC Protocols

Custom /
Standard







	1-50 kg	50-100 kg	> 100 kg
Standard	1	1	**4**
Custom	**6**	1	0
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Weight ≈ Money

=> Inaccessible Standard

TC Protocols

> *Inaccessible Standard*

TC Protocols

“ Inaccessible Standard

Grown over
Decades

TC Protocols

“ Inaccessible Standard

Grown over Decades

Unknown Requirements

TC Protocols

“ Inaccessible Standard

Grown over Decades

Unknown Requirements

No Best Practices

TC Protocols

> *Inaccessible Standard*

Grown over Decades

Unknown Requirements

No Best Practices

Few Open-Source Implementations

TC Protocols

> *Inaccessible Standard*

Grown over Decades

Unknown Requirements

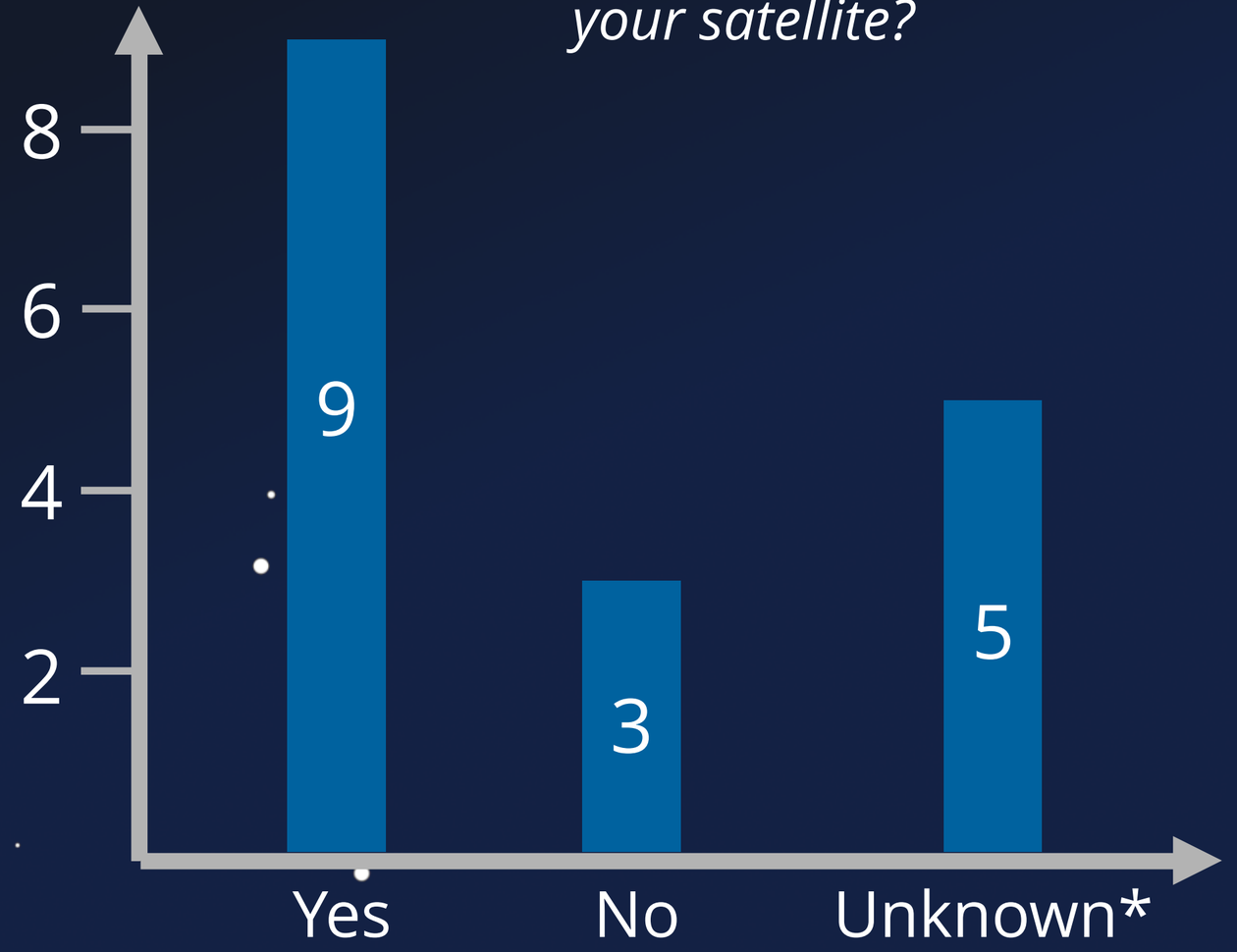
No Best Practices

Few Open-Source Implementations

"Guideline" Standards

TC Protection

Question: *Are **any measures deployed** to prevent 3rd parties from controlling your satellite?*

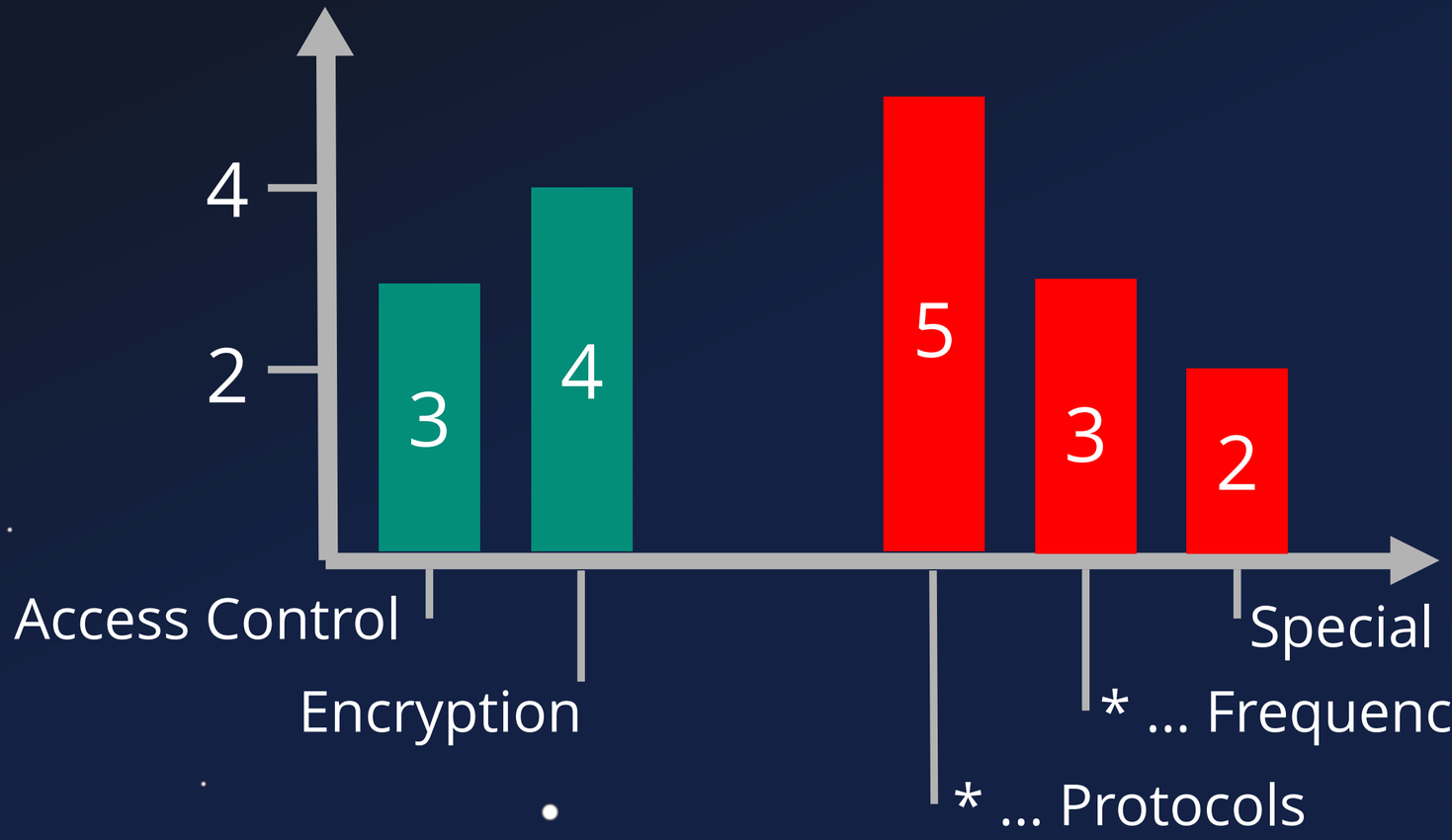


Unknown*:

Prefer not to say / Don't know

TC Obscurity

Question: ***What measures*** *are deployed to prevent 3rd parties from controlling your satellite? (Multiple Answers)*



Challenges

Security by Obscurity

Challenges

Security by Obscurity

Emergency Recovery

Challenges

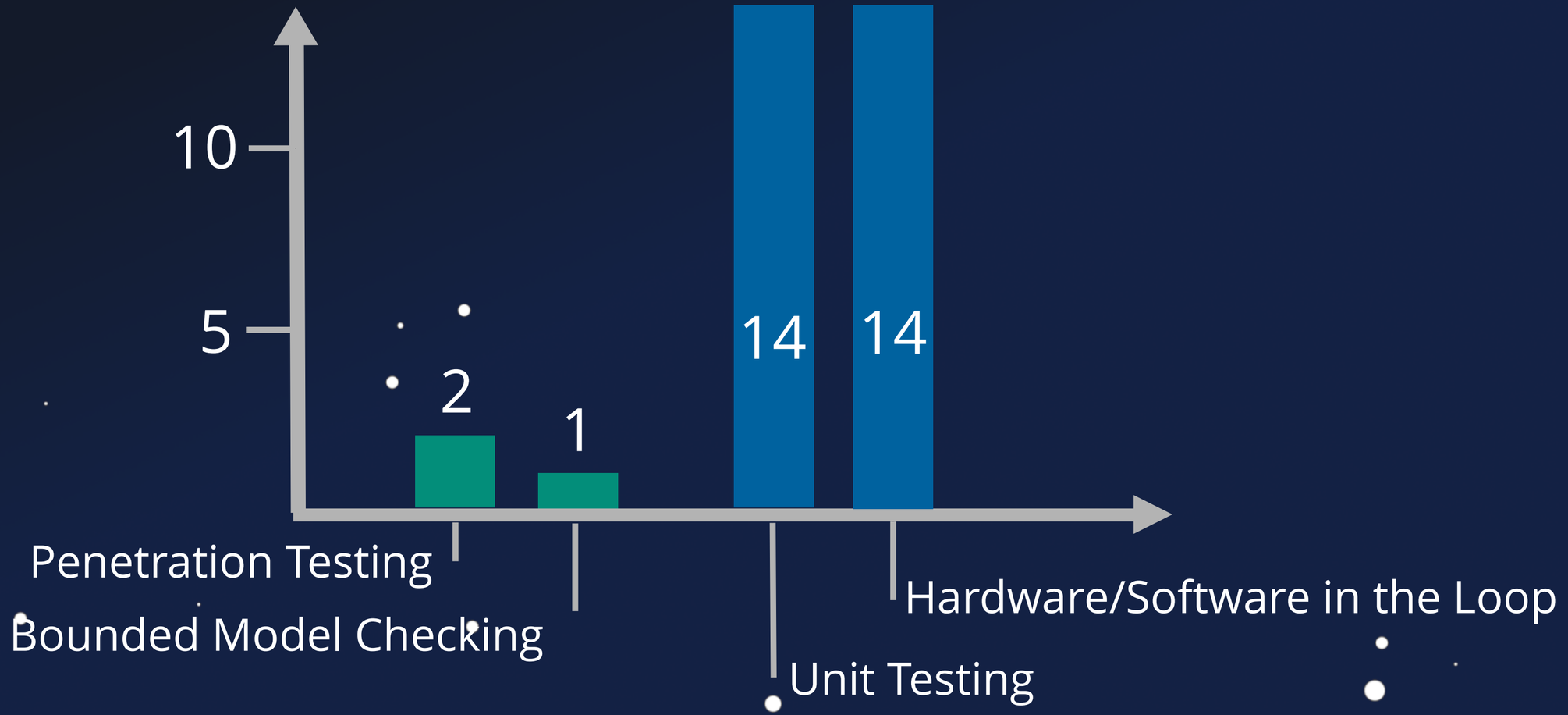
Security by Obscurity

Emergency Recovery

Technical Challenges

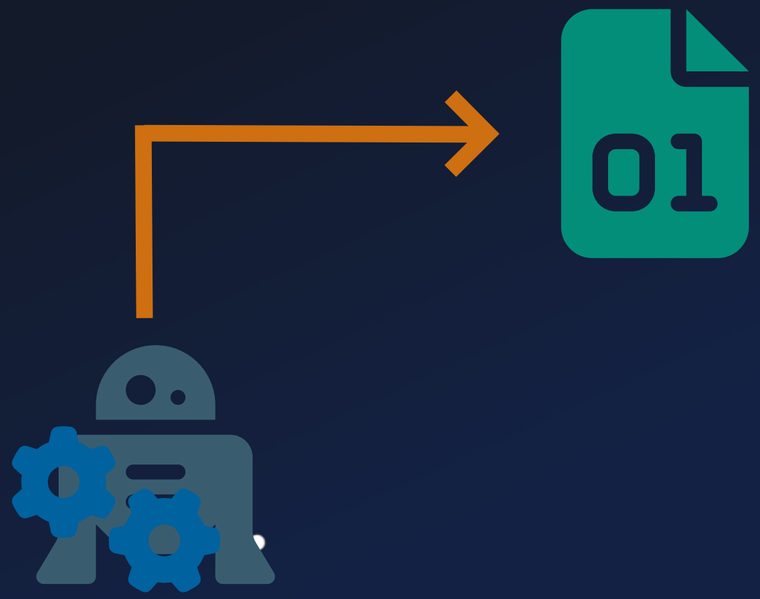
Security Testing

Question: ***Which**, if any, **methods, tools or techniques** were used to ensure/improve code quality? (Multiple Answers Possible)*



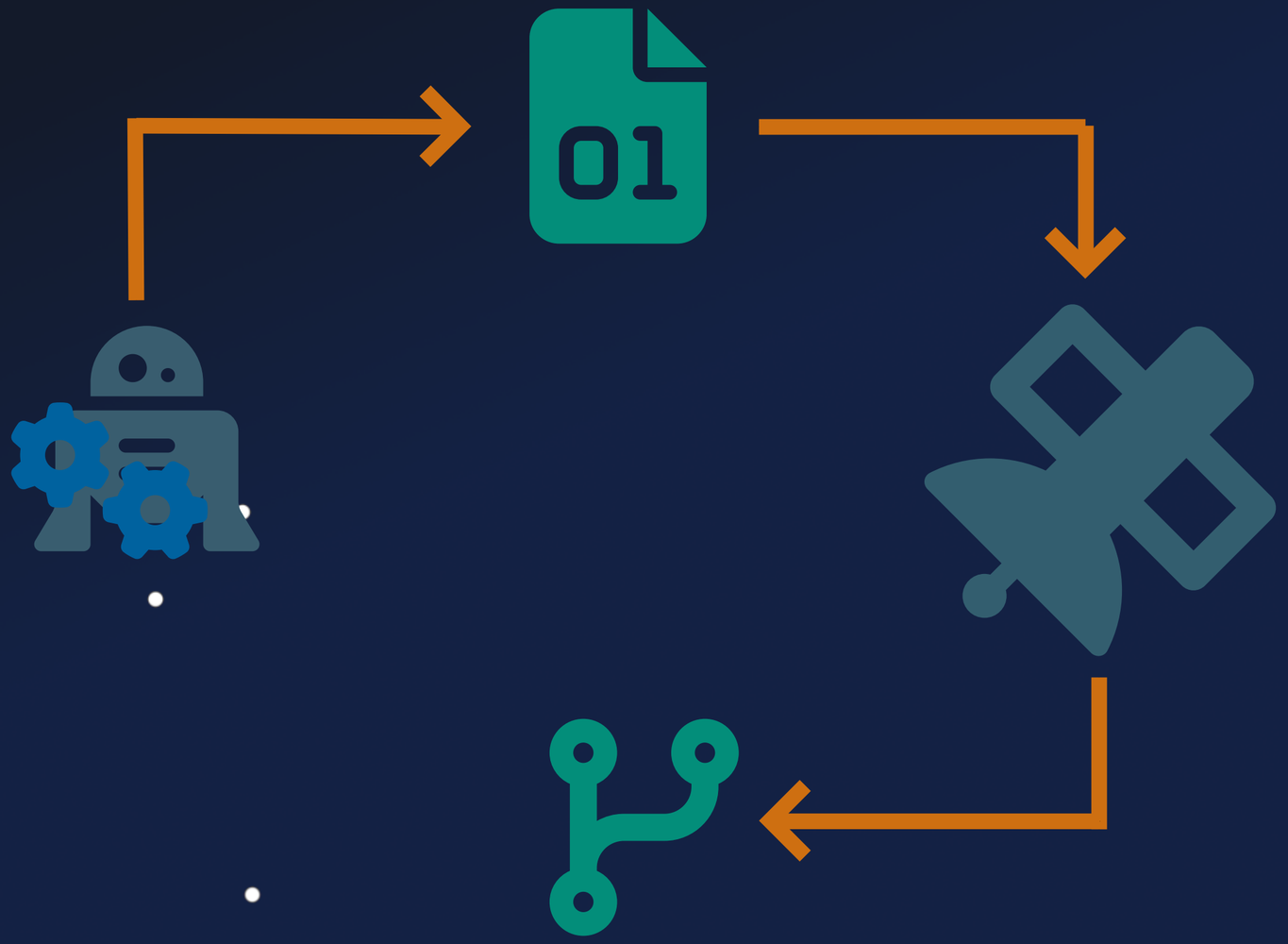
Fuzzing

Fuzzing

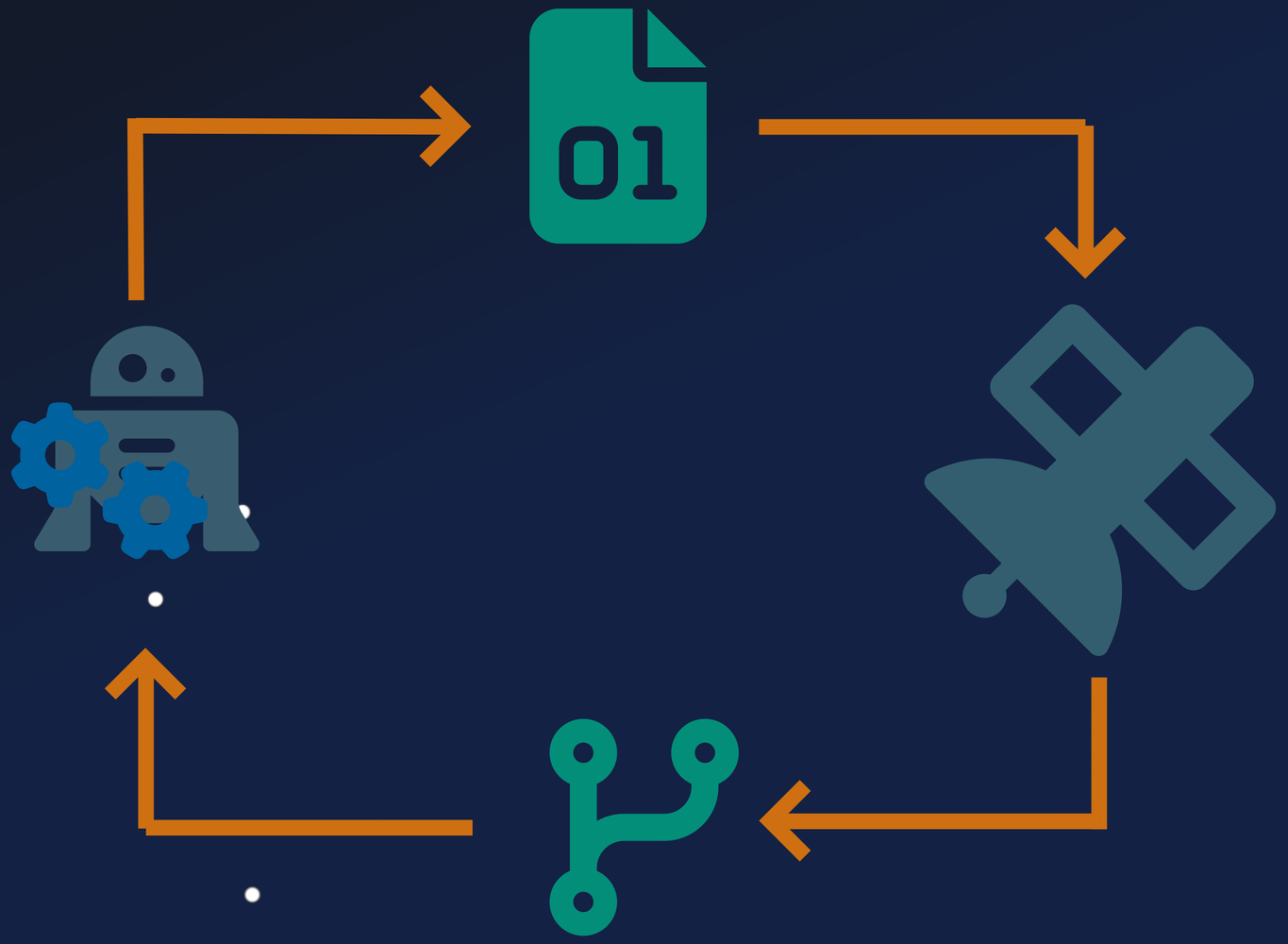


Fuzzing

Fuzzing



Fuzzing



*“ But it's different for *my* satellite*

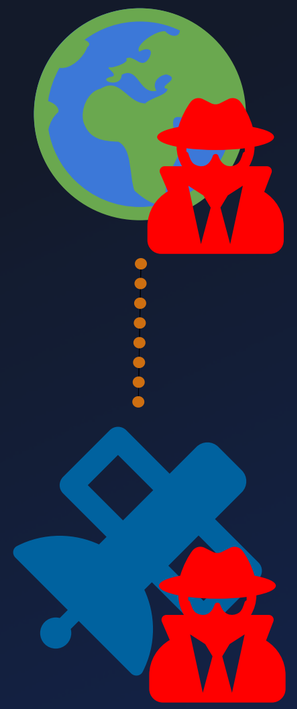
Impact

1. Hack a Satellite

2. ???

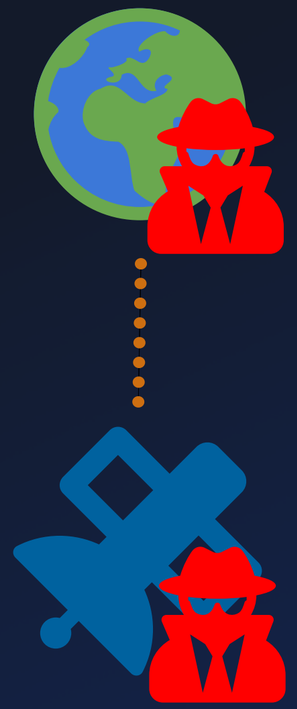
Scenarios

Scenarios



Orbital Access

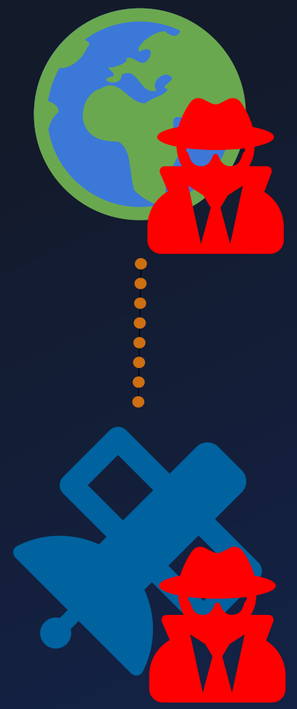
Scenarios



Orbital Access

1. Attacking Inter-Sat Links

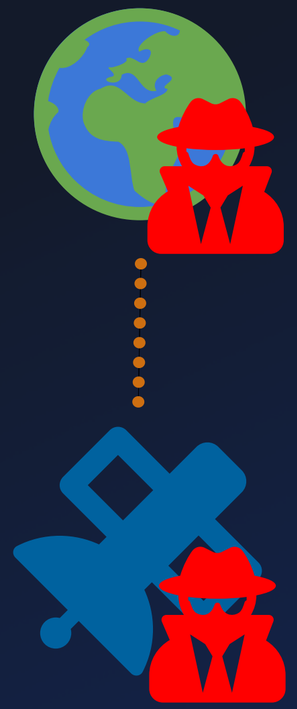
Scenarios



Orbital Access

1. Attacking Inter-Sat Links
2. Orbital Traffic Interception

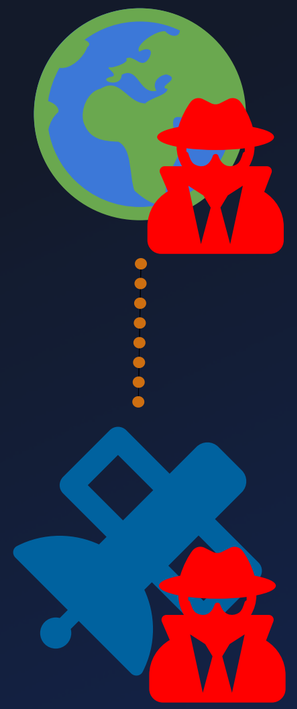
Scenarios



Orbital Access

1. Attacking Inter-Sat Links
2. Orbital Traffic Interception
3. Orbital Denial-of-Service

Scenarios



Orbital Access

1. Attacking Inter-Sat Links
2. Orbital Traffic Interception
3. Orbital Denial-of-Service
4. Kessler Syndrome

Attacker Perspective

Hack-a-Sat

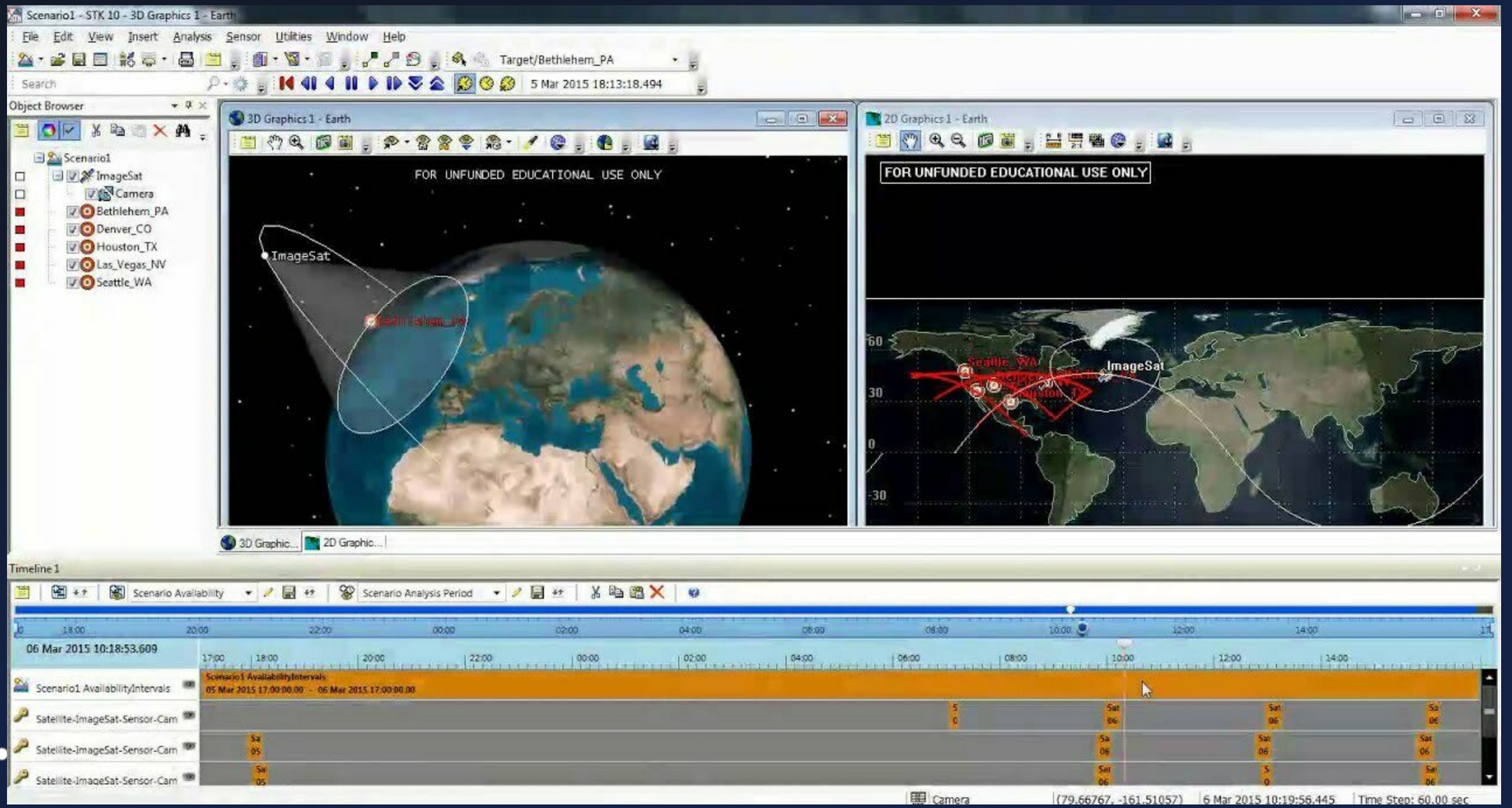

HACK-A-SAT 2
THE GOOD, THE BAD AND THE CYBER-SECURE


4


Flux *** Repeat *** Rocket ***


KRAUT SAT

Math? Math!


Scenario1 - STK 10 - 3D Graphics 1 - Earth
File Edit View Insert Analysis Sensor Utilities Window Help
Target/Bethlehem_PA
5 Mar 2015 18:13:18.494
Object Browser
Scenario1
ImageSat
Camera
Bethlehem_PA
Denver_CO
Houston_TX
Las_Vegas_NV
Seattle_WA
3D Graphics 1 - Earth
FOR UNFUNDED EDUCATIONAL USE ONLY
ImageSat
2D Graphics 1 - Earth
FOR UNFUNDED EDUCATIONAL USE ONLY
60
30
0
-30
ImageSat
3D Graphic...
2D Graphic...
Timeline 1
Scenario Availability
Scenario Analysis Period
06 Mar 2015 10:18:53.609
Scenario1 AvailabilityIntervals
Satellite-ImageSat-Sensor-Cam
Satellite-ImageSat-Sensor-Cam
Satellite-ImageSat-Sensor-Cam
Camera
(79.66767, -161.51057)
6 Mar 2015 10:19:56.445
Time Step: 60.00 sec

HACK-A-SAT CONTACT WINDOW TIMELINE

Contact Window Deadline for Team Submissions

Overnight Deadline for Team Submissions

Contact Window

Game Hours

Off Hours

ACS

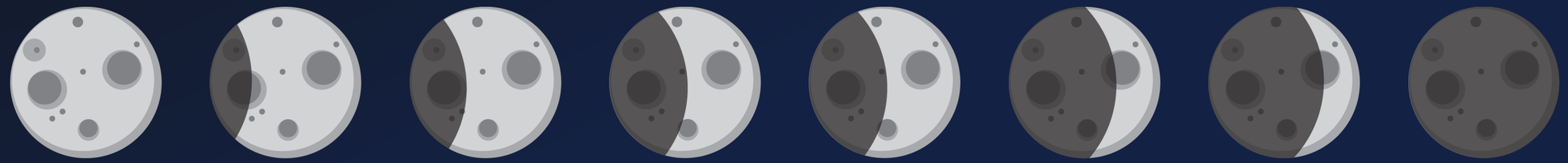
FRI GAME START 9AM

FRI GAME STOP 7PM

SAT GAME START 10AM

SAT GAME STOP 6PM

Lesson Learnt



Lessons Learnt

Firmware Attacks on Satellites are a Thing

ViaSat Incident != Satellite Firmware Attack

Common Sat Protocols lack Security

Security by Obscurity

Lessons Learnt

Missing TC Protection

Missing State-of-the-Art Defenses

Attacker Access to Orbit as Staging Ground

Unknown Consequences

Thanks!

- Firmware Attacks on Satellite
- Satellite Exploitation Objectives
- Three Satellite Case Studies
- Satellite Developer Survey
- Impact beyond Vulnerable Satellites

@jwillbold

/jwillbold

Johannes Willbold - johannes.willbold@rub.de

[1] ESTCube-1 Image: https://www.eoportal.org/satellite-missions/estcube-1
[2] OPS-Sat Image: https://www.esa.int/ESA_Multimedia/Videos/2019/12/OPS-SAT_ESA_s_flying_lab_open_to_all
[3] Flying Laptop Image: https://www.irs.uni-stuttgart.de/en/research/satellitetechnology-and-instruments/smallsatelliteprogram/flying-laptop/

Discussion

Future Research

Ecosystem Players

Rsearch Advice

Future Research

Trust Hierarchy

Future Research

Trust Hierarchy
Satellites

Future Research

Trust Hierarchy
Satellites

Trust Hierarchy
User Segment

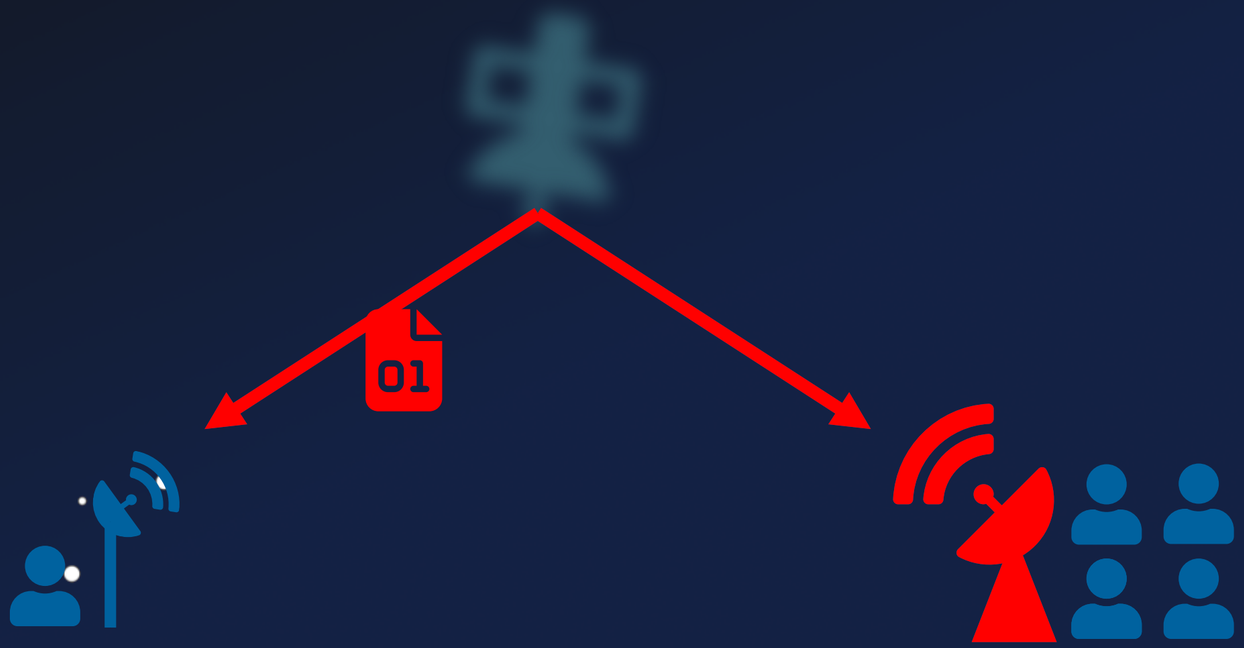
Future Research

Trust Hierarchy
Satellites

Trust Hierarchy
User Segment

Future Research

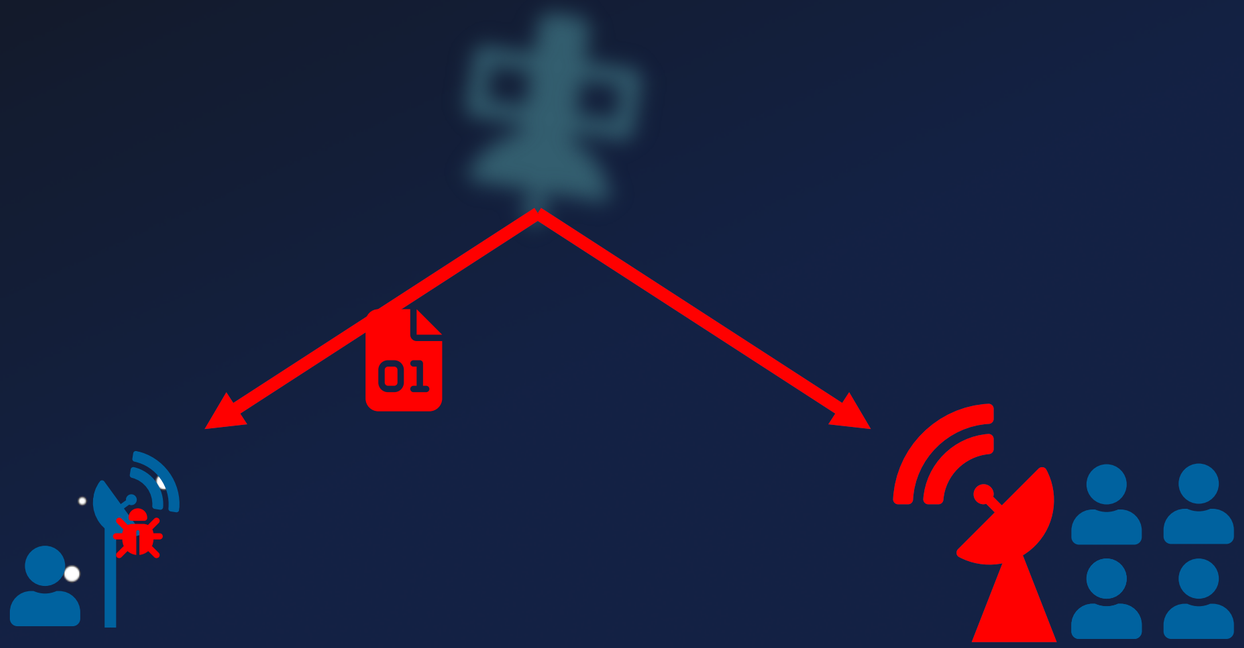
Trust Hierarchy
Satellites



Trust Hierarchy
User Segment

Future Research

Trust Hierarchy
Satellites



Trust Hierarchy
User Segment