Firefly: Spoofing Earth Observation Satellites through Radio Overshadowing

Edd Salkield [1] Joshua Smailes [1] Sebastian Köhler [1] Simon Birnbach [1]
Richard Baker [1] Martin Strohmeier [2] Ivan Martinovic [1]

[1] Systems Security Lab, University of Oxford

[2] Cyber-Defence Campus, armasuisse Science + Technology

NDSS SpaceSec 2023

Challenges of unauthenticated satellites

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Challenges of unauthenticated satellites

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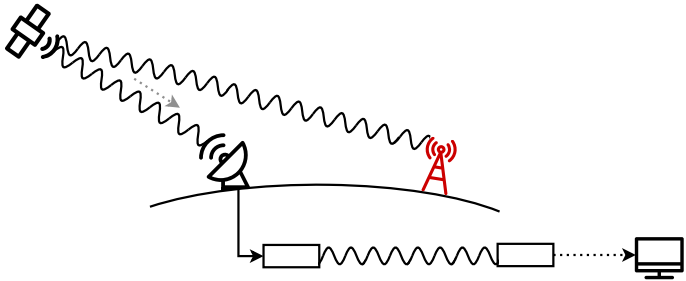
Insecure Earth Observation Satellites

Satellites with insecure downlinks include:

- **Fire detection and management**, e.g., Terra, Aqua
- Geospatial intelligence, e.g., Landsat-7..9
- Weather monitoring, e.g., GOES-14..17, FengYun series
- Infrared sensing, e.g., Metop-A,B
- Climate monitoring, e.g., Suomi-NPP

Implications

Data secrecy



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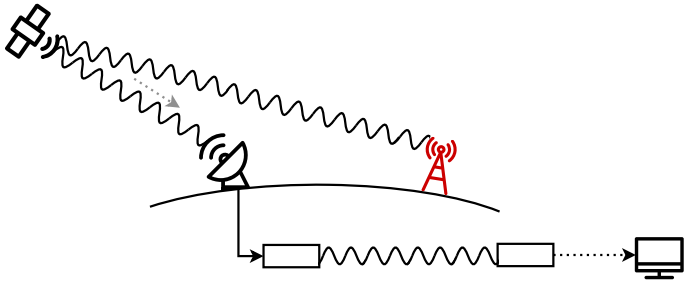

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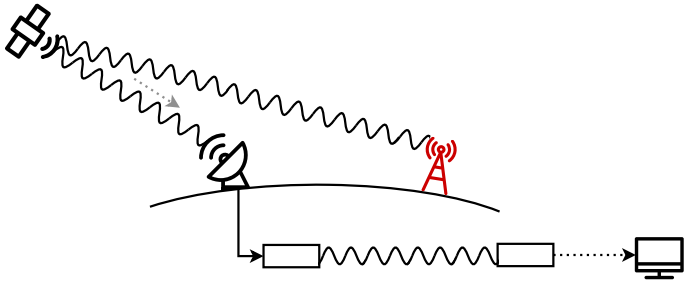

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- Read confidential maritime data[1] and internet traffic[2]

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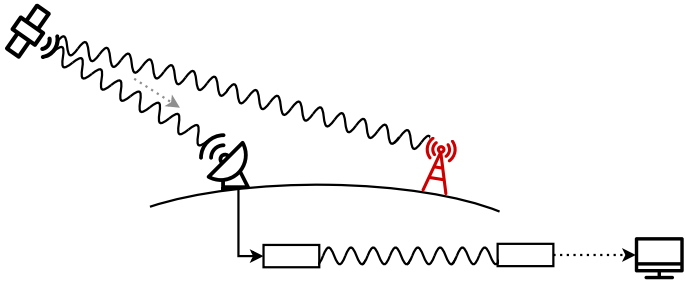

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- Eavesdrop on Iridium traffic and calls [3]

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[3] muccc "*Iridium Toolkit*" `https://github.com/muccc/iridium-toolkit`

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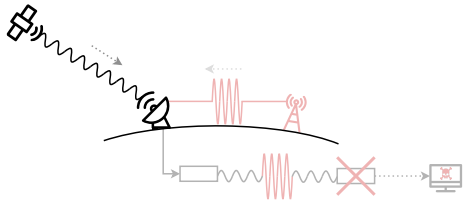
Data authenticity and integrity



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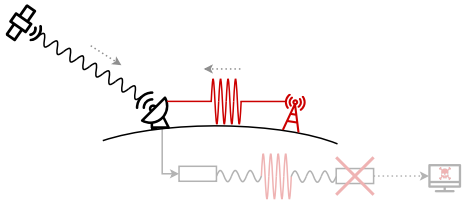

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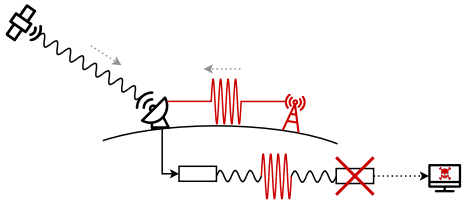

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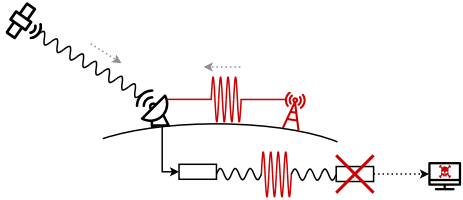

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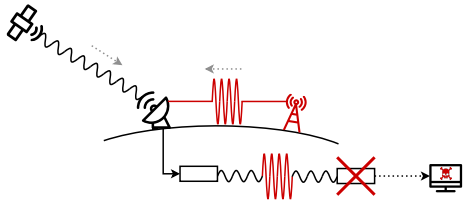

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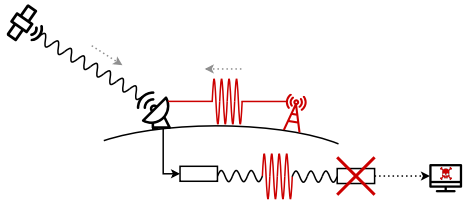

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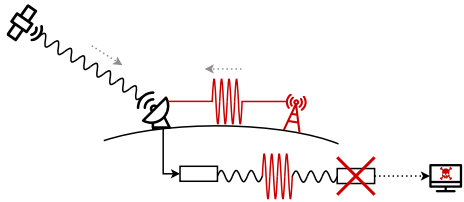

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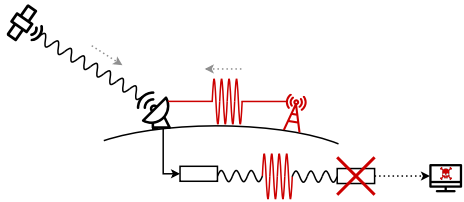

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RQ: What can the attacker achieve by exploiting the unauthenticated channel of these specific systems?

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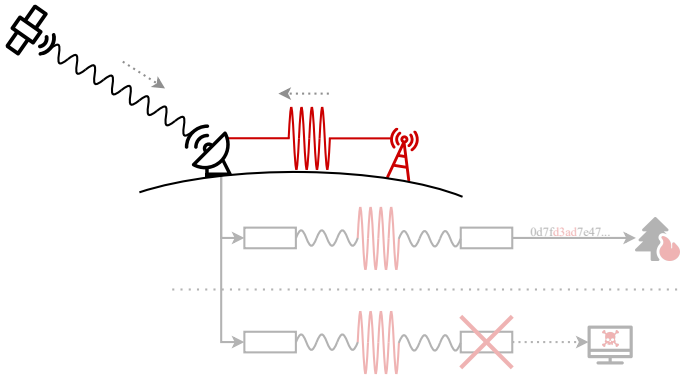
Threat model



Attacker transmits counterfeit signals in the vicinity of the receiver, to:

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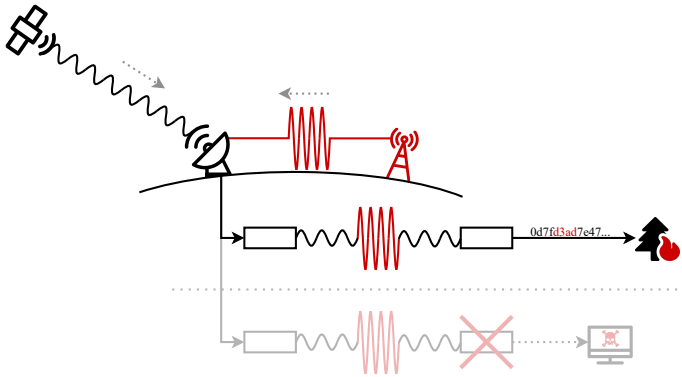

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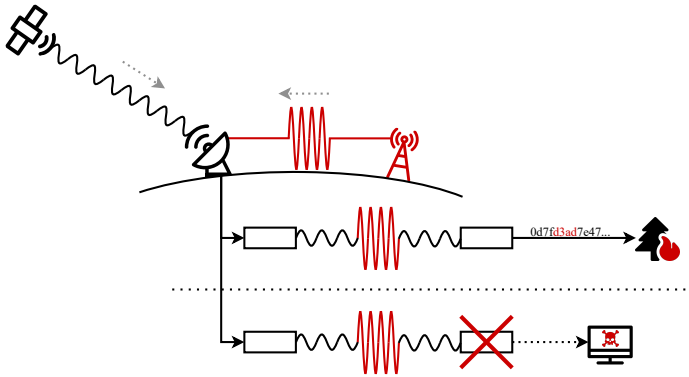

Attacker transmits counterfeit signals in the vicinity of the receiver, to:

- Affect the satellite-derived datasets
- Exploit or disrupt downlink processing stages

Attacker capabilities

Estimated cost

Hardware component	Cost
Software-defined radio	598 USD[1]
X-Band upconverter	~100 USD[2]
X-Band amplifier	1,638 USD
Compatible antenna	431 USD
Total	~3,000 USD

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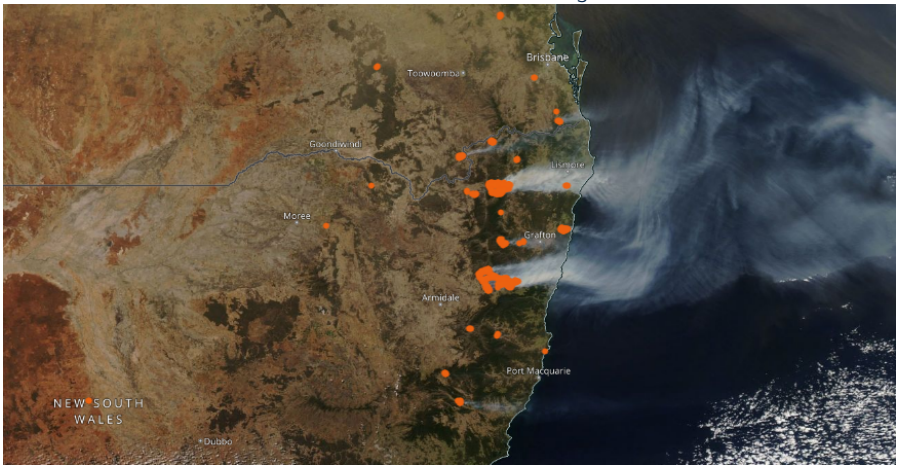
Case Study: Forest fire detection in FIRMS

NASA's global fire detection service



The 2019 Australia bushfires as seen from Aqua's MODIS instrument, annotated with the *Fires and Thermal Anomalies* dataset on NASA's worldview.

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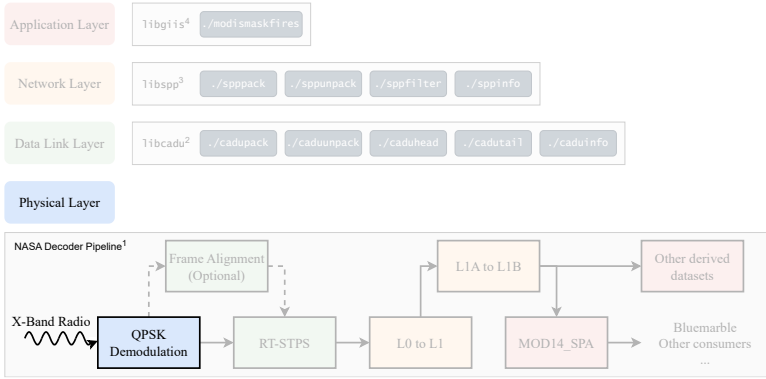
Experiment setup



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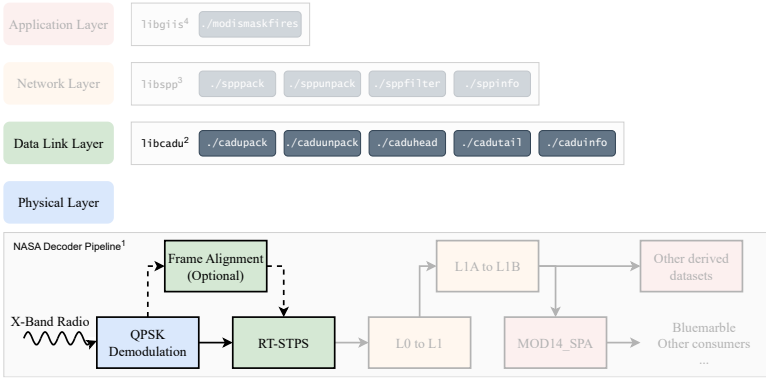

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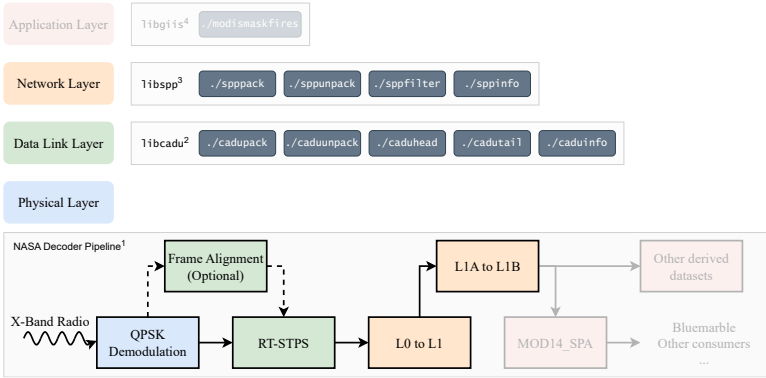

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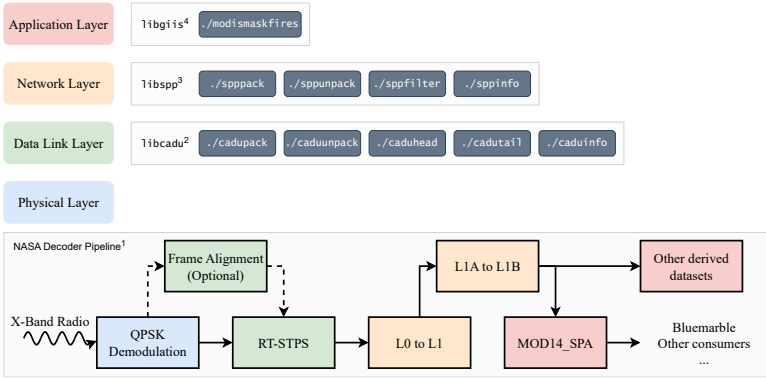

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Attack overview

Our attack

- Obtain legitimate data from digital archive[1]

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Affecting the derived dataset

Packet structure

Primary Header		Secondary Header					Data Zone			
...	Packet Length	Time Tag	...	Packet Type	Scan Count	Mirror Side	...	Frame Count	...	Data Field	Checksum

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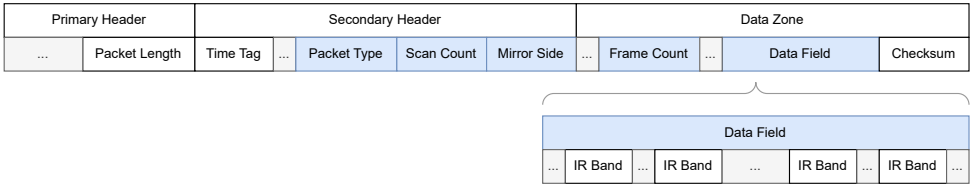

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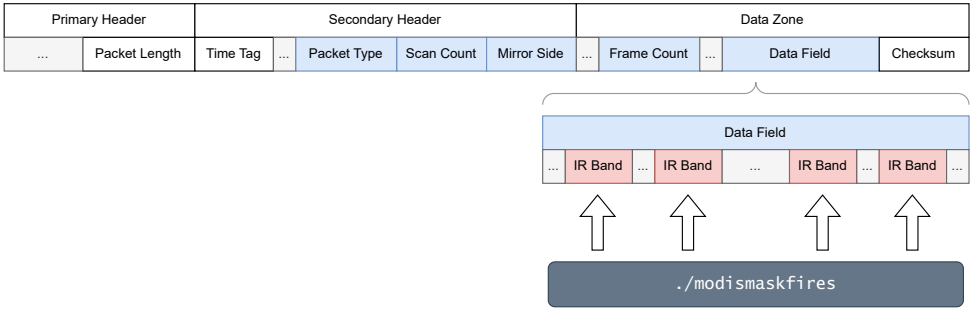
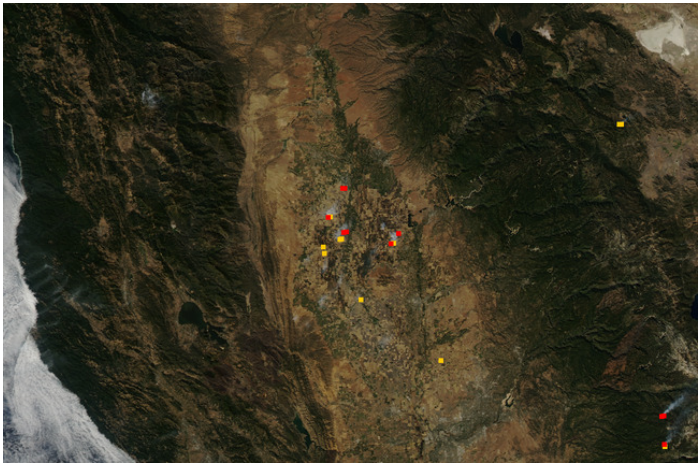


Affecting the derived dataset

Attack consequences



Original image.

Affecting the derived dataset

Attack consequences

Masking existing fires.

Affecting the derived dataset

Attack consequences

Fine-grained control over fire injection.

Exploiting the decoder

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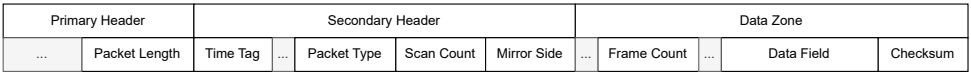

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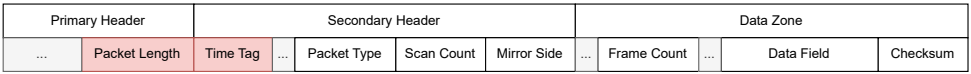

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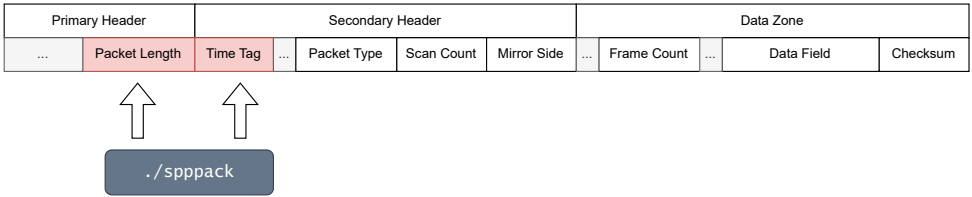

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            --app-id aqua_modis \
  > bad_packet.PDS
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Further vulnerabilities have been discovered since submission

Countermeasures

Cryptography should be required in future satellites

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Backwards-compatible countermeasures:

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Backwards-compatible countermeasures:

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- Multi-receiver data comparison
- Timing analysis[2]
- Physical-layer fingerprinting[3]

Existing countermeasures are effective, but aren't viable in all scenarios

[2] Jedermann et. al. (2021) "*Orbit-based Authentication Using TDOA Signatures in Satellite Networks*"
[3] Oligeri et. al. (2022) "*PAST-AI: Physical-Layer Authentication of Satellite Transmitters via Deep Learning*"

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- Analyze the effectiveness of proposed overshadowing countermeasures

SSL
Systems Security Lab

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- provided the source code required to manipulate the packet data and structure.
- confirmed that only a moderate budget is required to perform these attacks.
- identified current countermeasures which significantly increase attack difficulty.

Thank you for your attention

Any questions?

Reach out to me at
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