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Firefly: Spoofing Earth Observation Satellites through Radio Overshadowing

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Trinity Term 2022

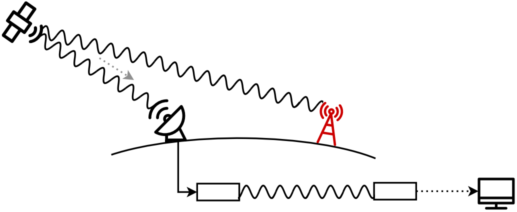
Challenges of unauthenticated satellites

- Many current satellites do not encrypt the downlink, due to:
  - Engineering constraints
  - Desire for public reception
  - Increased power budget and costs
  - Legacy systems, and backwards compatibility with them
- Other satellites are decryptable, due to:
  - Insecure cryptosystems [1]
  - Leaked keys [2]

[1] COMS-1 uses single DES `https://vksdr.com/lrit-key-dec/`
[2] GK-2A keys embedded in published source code `https://vksdr.com/xrit-rx/`

Implications

Data secrecy



Using only an off-the-shelf SDR and open source software, attackers can:

- Read confidential maritime data and internet traffic, Pavur et. al [**?**, **?**]
- Eavesdrop on Iridium traffic and cals [**?**]

Certain satellites designed to be unencrypted, e.g.

- EOS fleet: Terra, Aqua, Aura, etc.
- Amateur radio satellites e.g. SO-50, QO-100
- Freeview TV

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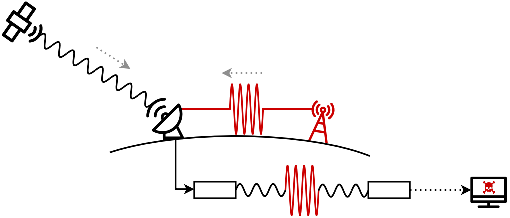
Implications

Data authenticity and integrity



Spoofing attacks have been shown against:

- GNSS to manipulate calculated location [**?**, **?**]
- Uplink to hijack the satellite or intrude on TV broadcasts [**?**, **?**]

However, no work considers the consequences of spoofing Earth Observation satellites.

Research question: What can the attacker achieve by exploiting the unauthenticated channel?

Implications

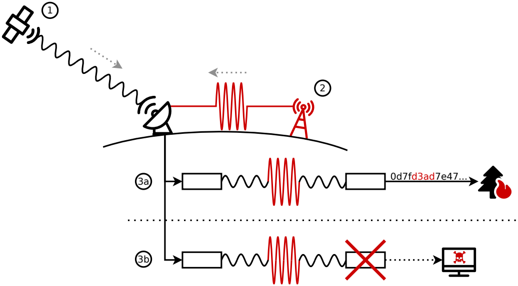
Unencrypted Earth Observation Satellites

Many Earth Observation satellites are unencrypted, including:

- **Fire detection and management** e.g. Terra, Aqua
- Geospatial intelligence e.g. Landsat-7..9
- Weather monitoring e.g. GOES-14..17, NOAA=15,18..21, FengYun series
- Infrared sensing e.g. Metop-A,B
- Climate monitoring e.g. Suomi-NPP

Threat model

Adversary's goal



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**
limeSDR	598 USD
X-Band transmitter	22, 800 EUR
Compatible antenna	6, 400 EUR
Total	~30, 000 EUR

Within the budget of a motivated hobbyist.

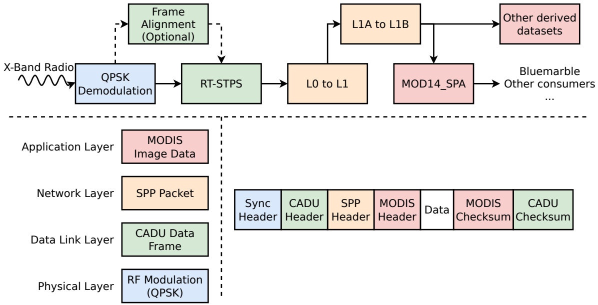
Case Study: Forest fire detection in FIRMS

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.

Case Study: Forest fire detection in FIRMS

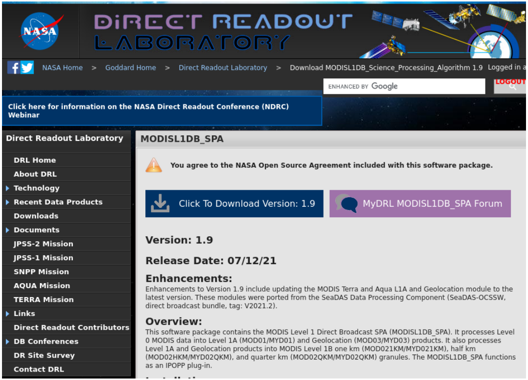
Experiment setup



We set up docker pipeline for the relevant parts of IPOPP

Exploiting processing stages

Obtaining the processing software



With a research account, anyone can download the entire set of decoding software from NASA's *Direct Readout Laboratory*

`https://directreadout.sci.gsfc.nasa.gov/`

Affecting the derived dataset

Key challenges

- Obtaining legitimate data
  - Beforehand – download from NASA distributed data archive
  - Live – set up custom receiver setup
- Processing it to add/remove artefacts
  - Reverse engineer the image format, and write an image manipulation program

Affecting the derived dataset

Data capture

Index of /archive/Science Domain/Level-0/MODIS Level-0/MODIS Aqua C6.1 - Level 0 Raw Instrument Packets (5 minutes)/2015/299/

Download Selected | See wget Download Command | Download Help | View as JSON | View as CSV

Multi-file downloads: Click individual table rows (or hold down Shift key for multiple) to select files followed by clicking "Download Selected" to confirm multi-file download

Select All		Last Modified	Size
.. Parent directory			
MYD00F.A2015299.0000.20152990300.000.PDS.bz2		2017-12-22 06:29	149.0
MYD00F.A2015299.0000.20152990300.001.PDS.bz2		2017-12-22 06:29	68.0 MB

https://ladsweb.modaps.eosdis.nasa.gov/archive/

Affecting the derived dataset

Data processing: image format reversing

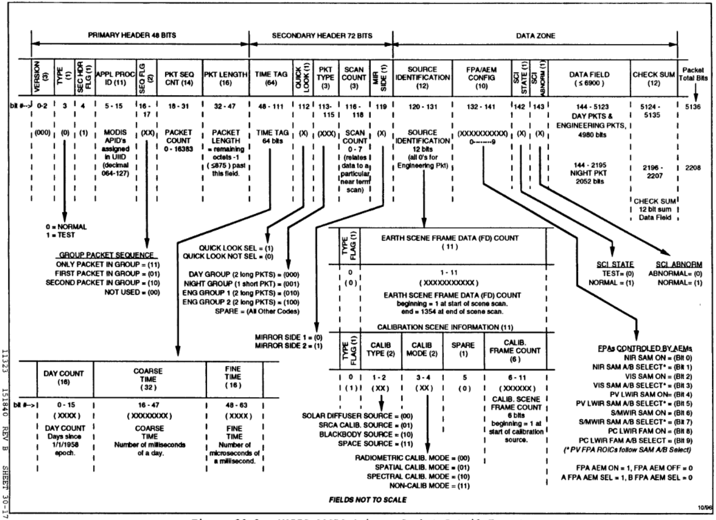


Figure 30-8. MODIS CCSDS Science Packet Detail Format

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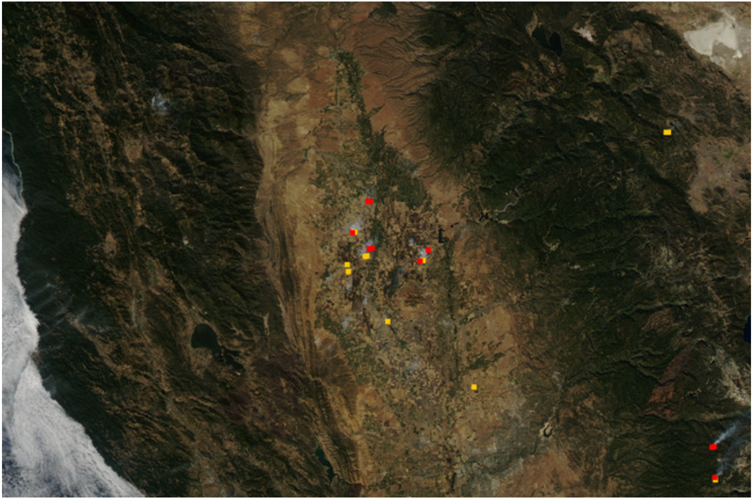
Affecting the derived dataset

Data processing: building protocol manipulation tools

TODO: find way of presenting the tools

Attack consequences

Affecting the derived dataset



Original image.

Attack consequences

Affecting the derived dataset

Masking existing fires.

Attack consequences

Affecting the derived dataset

Fine-grained control over fire injection.

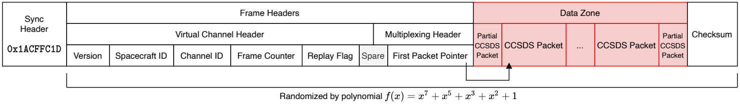
Exploiting processing stages

Key challenges

- Obtain downlink decoder software and perform security audit
  - Look for possible exploits around manual memory management and execution boundaries
- Construct payload packet to trigger vulnerability chain
  - Violate assumptions about the protocol headers

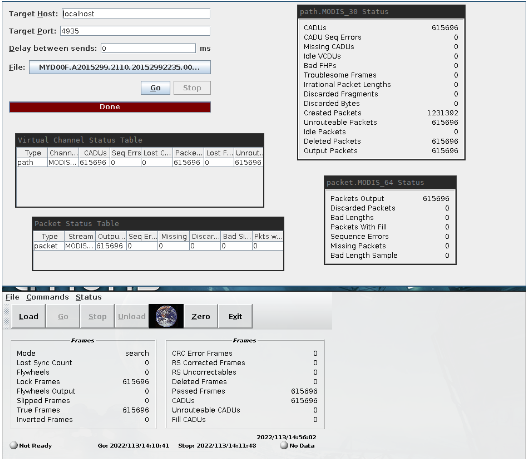
Exploiting processing stages

Construct payload packet



Attack consequences

Exploiting the processing stages



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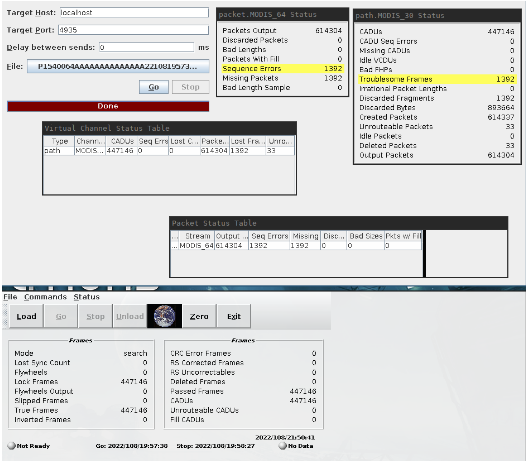
Attack consequences

Exploiting the processing stages



Countermeasures

Multi-receiver data comparison

TODO: citations Look for artefacts of tampering in the packets, and compare packets from multiple groundstations

- Certain systems already have multiple receiver stations
- Protects against decoder exploitation
- Doesn't require any hardware modifications to the receiver

Countermeasures

Timing analysis

- Triangulating the source effective in other systems such as aircraft
- Calculated position can be compared against orbital parameters
- Requires accurate clock synchronisation and multiple receivers

Countermeasures

Physical-layer fingerprinting

- Analyse properties of the legitimate/overshadowed signal
- Only effective on the downlink
- Traditional approaches like analysing signal-to-noise may prove effective
- New ML approaches starting to be created (PAST-AI)

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Conclusion

Our paper...

- presents a demonstration of byte-level spoofing against NASA's forest fire detection system.
- provides the source code required to manipulate the packet data and structure.
- confirms that only a moderate budget is required to perform these attacks.
- identifies current countermeasures which significantly increase attack difficulty.