Satellite Ground Station & RF Down Converter Frontend Subsystem Proposal

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ECE 445

February 13, 2026

1   Problem

There are over 14,000 satellites orbiting the Earth. From real-time weather images, pictures of our Sun, HAM radio, to leaked unencrypted military communications, each satellite is transmitting a variety of readily available data. Some of this data can even be life saving or critical to our infrastructure. With such intriguing information available, it is no wonder why there has been a growing interest in satellite communications for so many different communities. However, accessing satellite data directly or indirectly typically requires either internet based services, expensive tracking hardware, RF experience, and a lot of manual setup. For off-grid users, remote communities, and students learning RF/satellite communication, this creates a large barrier: even if the satellites are transmitting overhead, it's hard to reliably aim an antenna, lock the signal, and turn that RF into usable decoded output.

Many relevant or interesting satellites, including those for weather, are low Earth orbiting (LEO), which require real-time tracking through the sky, either manually or a motorized mount. There are no commercial and affordable hands-free, motorized antenna mounts, and none of them are truly hands-off and automated. They also usually transmit in L-band and/or in S-band. So even though most of the equipment to start can be homemade or cheap, such as an antenna, some free software, and a basic software defined radio dongle (like a RTL-SDR), these microwave band signals can still be hard or impossible to properly receive and decode due to limited range. An MMDS or frequency downconverter is required for both a cheap option like an RTL-SDR and even a step up to a $300 Hack RF One. Additionally, there are not many commercial and affordable downconverters available As a result of both of these obstacles, receiving any updated critical/useful data is often impractical, inconsistent, or too costly for most people to try.

2   Solution

Our overall goal is to help make radio and satellite tracking/reception more accessible for educators, researchers, remote communities, survivalists, and radio enthusiasts alike. To accomplish part of this task, we seek to address two of the most inaccessible and unaffordable aspects: live tracking and making those microwave transmissions receivable by cheaper SDR's. More specifically, we will create an affordable automatic, motorized satellite tracker/receiver and a custom S-band frequency downconverter.

High-Level Requirements

- RF frontend can downconvert an L-band signal with $> 20dB$ SNR.
- Motorized antenna can track an LEO satellite for 10 minutes while above the horizon.
- Stored signal can be decoded by Satdump.
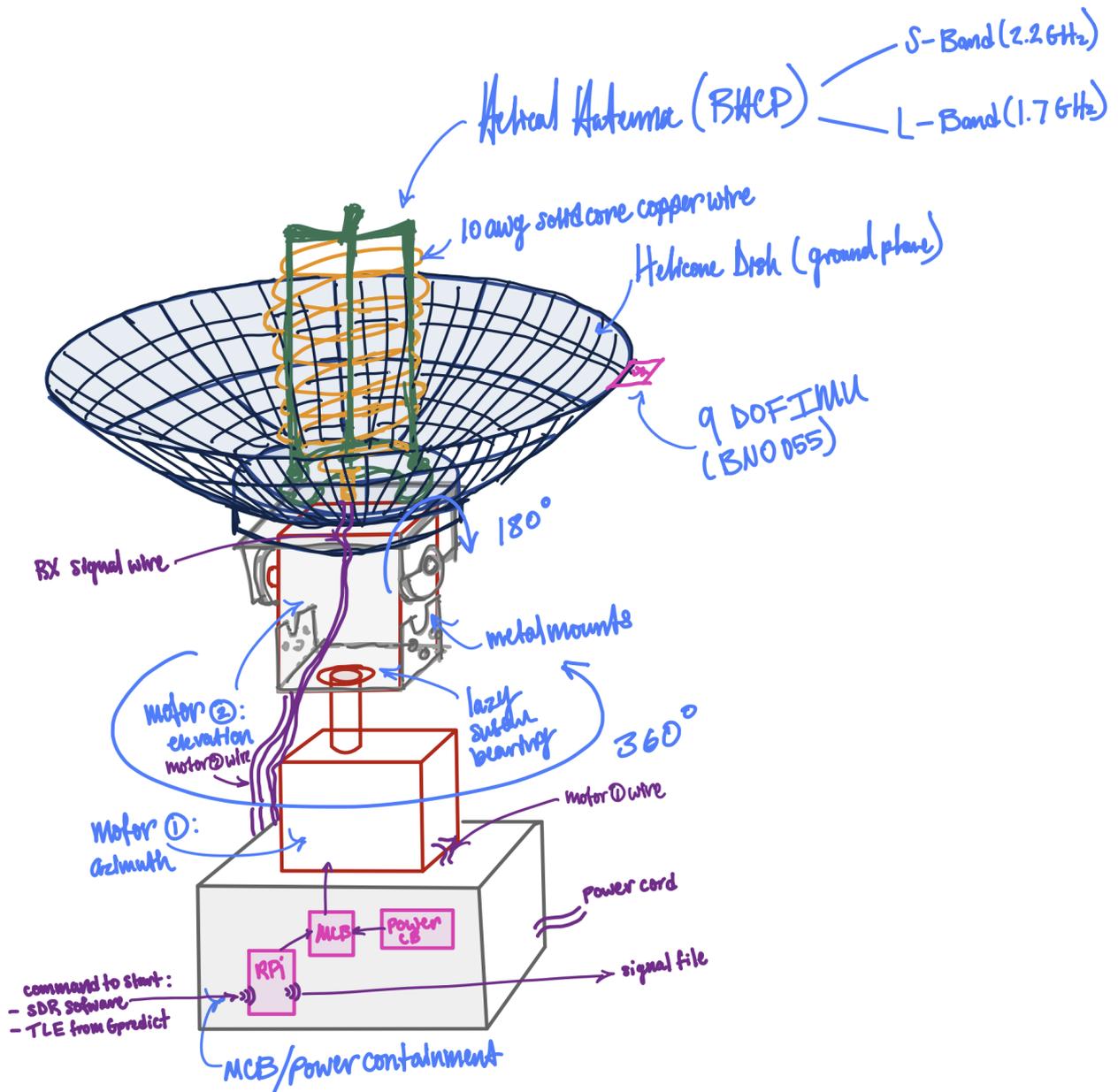
2.1 Ground Station

2.1.1 Design

Figure 1: Ground Station Overall Design

2.1.2 Block Diagram

2.2 Subsystem Overview

Helicone Dishcone Antenna: Receives incoming satellite RF energy and couples it into the RF front end via a 50 Ω coax interface. The antenna is mechanically mounted on the azimuth/elevation platform so pointing is provided by the motorized mount.

S-Band RF Frontend (LNA & MMDS): Amplifies and downconverts the received S-band signal into a frequency range the SDR can digitize. It interfaces to the antenna (RF in) and to the SDR dongle (RF/IF out), both as 50 Ω ports.

Software Defined Radio (SDR) Dongle: Digitizes the RF/IF output from the RF frontend and streams
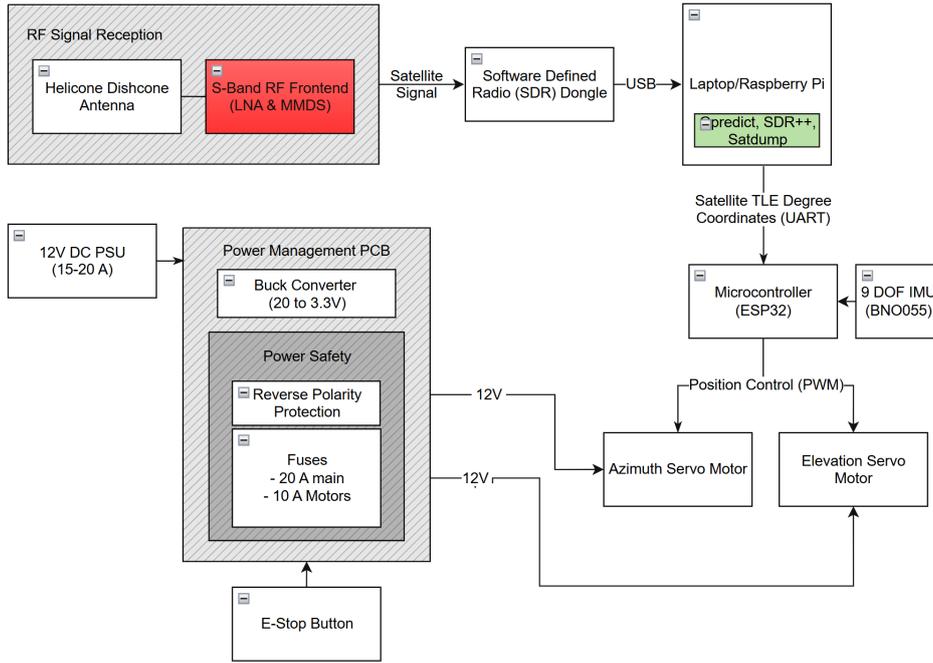
Figure 2: Ground Station Block Diagram

IQ samples to the host computer over USB.

Laptop/Raspberry Pi (Gpredict, SDR++, Satdump): Runs tracking TLE & decoding software, processes IQ data, and generates pointing commands from satellite predictions. It interfaces to the SDR dongle via USB and sends azimuth/elevation degree commands to the ESP32 via UART.

Microcontroller (ESP32): Receives azimuth/elevation commands, reads orientation feedback, and outputs motor control signals to aim the antenna. It interfaces to the laptop/Raspberry Pi (UART), IMU (I^2C), and servos (PWM).

9-DOF IMU (BNO055): Provides orientation/heading feedback used to correct pointing and reduce drift. It interfaces to the ESP32 over I^2C and is powered from the logic rail.

Azimuth Servo Motor: Rotates the antenna platform in azimuth to track targets. It receives PWM control from the ESP32 and 12 V motor power from the power management PCB.

Elevation Servo Motor: Tilts the antenna in elevation to track targets. It receives PWM control from the ESP32 and 12 V motor power from the power management PCB.

12 V DC PSU (15–20 A): Provides the primary 12 V power source for the system and feeds the power management PCB.

Power Management PCB (Buck + Power Safety): Distributes 12 V to motors, generates regulated logic power, and provides protection (fuses, reverse polarity protection, and E-stop integration). It interfaces to the PSU (12 V input), ESP32/IMU (logic rail), and servos (12 V motor outputs).

E-stop Button: Provides immediate removal of motor power during faults or unsafe motion. It interfaces to the power management PCB and interrupts the motor power path.

2.3 Subsystem Requirements

Helicone Dishcone Antenna: This block contributes to the overall design by enabling the high-level requirement of receiving satellite signals. It interfaces to the RF frontend via a 50 Ω coax output. Requirements: (1) operate over the target S-band receive range; (2) present a 50 Ω interface; (3) be mechanically mountable to the azimuth/elevation platform without loosening during motion.

S-Band RF Frontend (LNA & MMDS): This block contributes to the overall design by converting 2–3.5 GHz signals into the SDR input range with usable SNR. Interfaces: 50 Ω RF in (from antenna) and 50 Ω RF/IF out (to SDR). Requirements: (1) provide sufficient net gain so the SDR sees a detectable signal (target: ≥ 15 dB net gain after losses); (2) maintain 50 Ω matching at input and output; (3) include filtering sufficient to reduce out-of-band energy and prevent SDR overload.

Software Defined Radio (SDR) Dongle: This block contributes to the overall design by converting the analog RF/IF into digital IQ samples for decoding. Interfaces: RF input from frontend and USB to host. Requirements: (1) accept frontend output frequency within SDR tuning range; (2) stream IQ continuously to the host for the duration of a pass (target: ≥ 10 min); (3) operate without saturation/clipping under expected input levels (gain must be adjustable).

Laptop/Raspberry Pi (Gpredict, SDR++, Satdump): This block contributes to the overall design by generating pointing commands and decoding/recording received data. Interfaces: USB from SDR and UART to ESP32. Requirements: (1) compute azimuth/elevation pointing from TLEs and time; (2) output pointing commands at a fixed update rate (target: ≥ 1 Hz) over UART; (3) sustain SDR processing/recording during a pass (target: ≥ 10 min).

Microcontroller (ESP32): This block contributes to the overall design by performing real-time pointing control and generating motor control waveforms. Interfaces: UART in (commands), I^{2}C to IMU, PWM to servos, and regulated logic power. Requirements: (1) UART link compatible with host (target: 115200 bps, 8N1, command updates ≥ 1 Hz); (2) generate stable servo PWM (target: 50–333 Hz, pulse width ~1–2 ms as required); (3) I^{2}C communication with IMU (target: 100–400 kHz); (4) enter a safe state on command loss (stop/hold last safe position).

9-DOF IMU (BNO055): This block contributes to the overall design by providing orientation/heading feedback to improve pointing accuracy and stability. Interfaces: I^{2}C to ESP32 and logic power. Requirements: (1) output orientation/heading at a usable rate (target: ≥ 10 Hz); (2) maintain reliable I^{2}C communication during motor motion; (3) operate from the regulated logic rail (3.3 V per module specification).

Azimuth Servo Motor: This block contributes to the overall design by providing azimuth rotation necessary to track satellites while above the horizon. Interfaces: 12 V power and PWM control from ESP32. Requirements: (1) operate from 12 V within rated range; (2) produce adequate torque to rotate the antenna/load without stalling; (3) track commanded position updates smoothly without uncontrolled oscillation.

Elevation Servo Motor: This block contributes to the overall design by providing elevation control necessary to maintain pointing during a pass. Interfaces: 12 V power and PWM control from ESP32. Requirements: (1) operate from 12 V within rated range; (2) produce adequate torque for elevation load (including margin); (3) track commanded position updates smoothly without uncontrolled oscillation.

12 V DC PSU (15–20 A): This block contributes to the overall design by supplying continuous and peak power required for the motors and electronics. Interface: 12 V output to power management PCB. Requirements: (1) output 12 V ±10% under load; (2) supply peak current without brownout during motor transients (target: ≥ 15 A); (3) provide short/overcurrent protection (supply-side and/or via main fuse).

Power Management PCB (Buck + Power Safety): This block contributes to the overall design by providing regulated logic power, distributing 12 V motor power, and enforcing electrical safety protections. Interfaces: 12 V input from PSU; 12 V motor outputs; regulated logic output to ESP32/IMU; E-stop integration in motor power path. Requirements: (1) distribute 12 V to motors with minimal drop (target: < 0.5 V drop at peak motor current); (2) provide regulated logic rail.

2.3.1 Components & Pricing

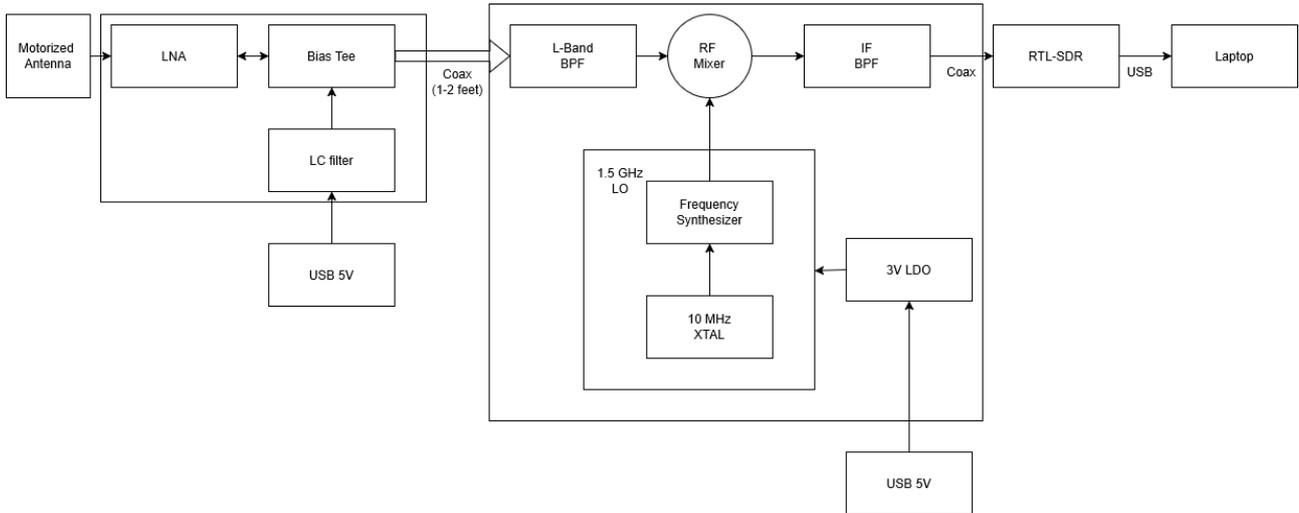| Item	Cost / Notes
RTL-SDR	$30
Antenna & dish parts	Usually negligible (could be free depending on sources)
Azimuth motor	$28; Product link
Elevation motor	$37; Product link
9-DOF IMU (BNO055)	$9
Lazy Susan bearing	$15
MCB & power management + parts	$8 + negligible extras
ESP32	$8
Mount brackets	Machine shop; cost TBD

Figure 3: RF Block Diagram

2.4 RF Down Converter Frontend Subsystem

The RTL-SDR has a maximum frequency of 1.75 GHz. In order to receive and demodulate S band signals we need to build a down converter that brings 2-3.5 GHz signals into range of the RTL-SDR. The down converter is an analog heterodyne: the RF signal from the antenna will be multiplied by a 1.5 GHz local oscillator signal using an rf mixer.

There will be two boards: LNA board connected directly to the antenna to reduce line attenuation, and down converter board that feeds into the RTL-SDR. Making the LNA and down converter into separate modules makes testing easier. Even if the more complex downconverter fails, the LNA module can be saved and used for L-band signals.

The LNA board will be power by USB 2.0 5V 500mA which will be filtered with an LC or pi filter to remove possible switching noise. Because the LNA is a MMIC it has rf out and power in at the same port. This will require a shunt inductor and DC blocking cap at the SMA output port while accommodating for impedance matching. USB power is sufficient because the LNA only needs 73mA for biasing and quiescent current input.

The downconverter board is an RF heterodyne. Before mixing a S band filter is required to remove signals that we are not targeting but have been picked up by the antenna. Without this intermodulation could overlap with our downconverted signal or the mixer could be overloaded.

In order to produce the LO we will require a frequency synthesizer IC and 10 MHz crystal clock. The synth is a phased lock loop and voltage controlled oscillator. Its output frequency is determined by the reference clock and the digital values on its bit shift pins. While these values can be controlled to change the LO frequency that would require a potentially noisy microcontroller next to a synth IC that has 36 pins. Like all RF components the synth needs to be impedance matched and the crystal needs to be biased in order to get 50 MHz.

The mixer in this design is an active RF filter with input buffer amplification. The alternative is a diode ring mixer which has attenuation. Using this active mixer avoids the need for post IF filter amplification.

The IF filter is required to remove the RF image (2.2 GHz + 1.5 GHz) and other possible spurious signals from the nonlinear effects of the mixer.

2.4.1 Components

Item	Part / Notes
RF LNA	SKY67151-396LF
S-band bandpass filter	BFCN-2360+
Active RF mixer	LT5560EDD#PBF
PLL synthesizer	LMX2531LQ1910E/NOPB
Oscillator reference	UCE4031035LK015000-10.0M
IF filter	LFCG-700+
Connectors	SMA
Passives	SMD RLC components

2.4.2 Tolerance Analysis of RF Frontend

One of the major issues that will affect the design of this section of the project is what the dBm of a GEO satellite signal will we receive with a proper 2.2 GHz right hand circular polarized helical antenna before amplification. The RTL-SDR accepts -20 to 0 dBm and has its own amplification to adjust noise floor and signal strength. Using the current listed amp, mixer, and filters we should get (when matched correctly and with minimal return loss) 20dB (lna) + 2dB (active mixer) - 3dB (bandpass filters) - ?dB (line attenuation). Therefore, if the raw satellite signal received by our antenna is less than -40 dBm, we would require a higher gain LNA or a second LNA at the end.

2.4.3 S-Band Satellite Options

Satellite	Downlink (MHz)	Orbit	NORAD ID	Purpose	What you can receive on S-band	Pol.
Hinode (Solar-B)	2256.00	LEO	—	Photographs Sun's surface	Low-rate science/telemetry	RHCP
Jason-3	2215.92	LEO	—	Measures global sea surface heights	Altimetry/mission data	RHCP/LHCP
BlueWalker 3	2245.00	LEO	—	Cellular broadband repeater	Encrypted 4G/5G data	RHCP
NOAA-20	2247.50	LEO	—	U.S. weather satellite	Telemetry	RHCP
DMSP	2237.50	LEO	—	Cold War-era U.S. military satellite	Real-time imagery	RHCP
DSCOVR	2215.00	GEO	—	Monitors solar wind; Earth imaging from deep space	Spacecraft telemetry / housekeeping frames	RHCP

3 Ethics

The motorized dish antenna mount does not directly violate any ethical or legal practices, but it still poses some electrical and mechanical hazards to users. The mount uses two 12V high-torque motors capable of producing a pinch or crush hazards. Though, no motion will be sudden nor is the voltage very high, there is some risk of unintended motion if given wrong or late degree inputs and shock/fire hazards if the electrical components are left unprotected from weather/foreign elements or surges/incorrect connections. Thus, we will integrate a visible E-stop switch, software prevention against sudden motion, mechanical guarding, some housing for components, fuses, and reverse polarity protection [1].

According to FCC regulations, radio compliance for our system means operating within the authorized frequency bands, power limits, and equipment authorization requirements that apply to the specific RF hardware and use case, and these laws are generally accepted or equivalent even outside the U.S. [2]. However, we will also have documentation making users aware of the legal limitations or protections with radio respective to their region.Although the motorized mount is primarily a mechanical/electrical subsystem, it interfaces with RF

equipment that must meet these rules. Even for a receive only device, we will follow good engineering practice and safe wiring to minimize radiated and conducted noise that could interfere with nearby electronics. For electrical and mechanical safety, we will follow hazard-based design practices reflected in modern equipment safety standards, such as insulation, enclosure integrity, and protection against overcurrent/overtemperature and fire risk. [1]. Although the device could be repurposed for some nefarious uses, such as tracking unauthorized targets, we will also reduce the incentive or ability to misuse the ground station by having firmware specific for tracking publicly available satellites/targets. Additionally, it will be framed as an educational, practical, and/or research application. Arguably, it is also part of our goal to encourage more awareness and safety surrounding digital communications, especially from satellites, by having such an accessible device. "Don't Look Up," an incredibly relevant study by a research team from the University of California San Diego (UCSD) and the University of Maryland (UMD), demonstrated that a substantial portion of GEO satellite links still carry sensitive traffic, even those by the U.S. military, in plaintext due to missing or inconsistent encryption [3]. They were able to document and protect this traffic by using a setup less than $800 [3]. Our setup will be several factors less expensive and focus on repairability and sustainability by having an open-source friendly design. Cybersecurity vulnerabilities have cost around $10.5 trillion in economic damage [4], and most companies and organizations rely on community-driven penetration testing, in forms of bug bounties or security research, to expose weak infrastructure and protect billions of people's sensitive information. This paper, and the cybersecurity community reinforce the importance of not only responsible, lawful use of a ground station but also making these tools accessible.

References

[1] "Iec 62368-1: Audio/video, information and communication technology equipment – safety requirements," International Electrotechnical Commission, 2018.

[2] "Federal communications commission (fcc) rules and regulations (47 cfr)," https://www.ecfr.gov/current/title-47, Federal Communications Commission, accessed 2026-02-13.

[3] W. M. Zhang, A. Dai, K. Ryan, D. Levin, N. Heninger, and A. Schulman, "Don't look up: There are sensitive internal links in the clear on geo satellites," in *Proceedings of the 32nd ACM Conference on Computer and Communications Security (CCS '25)*, 2025.

[4] S. Morgan and C. Ventures, "Official cybercrime report 2025 (cybercrime predicted to cost the world $10.5 trillion in 2025)," https://cybersecurityventures.com/official-cybercrime-report-2025/, 2025, accessed 2026-02-13.