NB-IoT over NTN for Wildlife Tracking: Architecture, Constraints, and Early Experiment Plan

A technical exploration of satellite-based narrowband IoT connectivity for remote marine animal monitoring, combining 3GPP standardized protocols with non-terrestrial networks to enable scalable wildlife conservation research.

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Why Wildlife Tracking from Space Matters

The Coverage Challenge

- 71% of Earth surface are oceans, many other key habitats have **no terrestrial connectivity**.
- Conservation and management depend on **long-term, reliable tracking data**.
- Satellite links let us **follow animals across borders and infrastructure gaps**.
- To protect ecosystems, we must **understand real marine life behavior in situ**, not just in captivity or near shore.

We can't protect what we don't measure

Talk Roadmap

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Satellite Communications for Constrained Devices

Overview of available technologies and fundamental trade-offs

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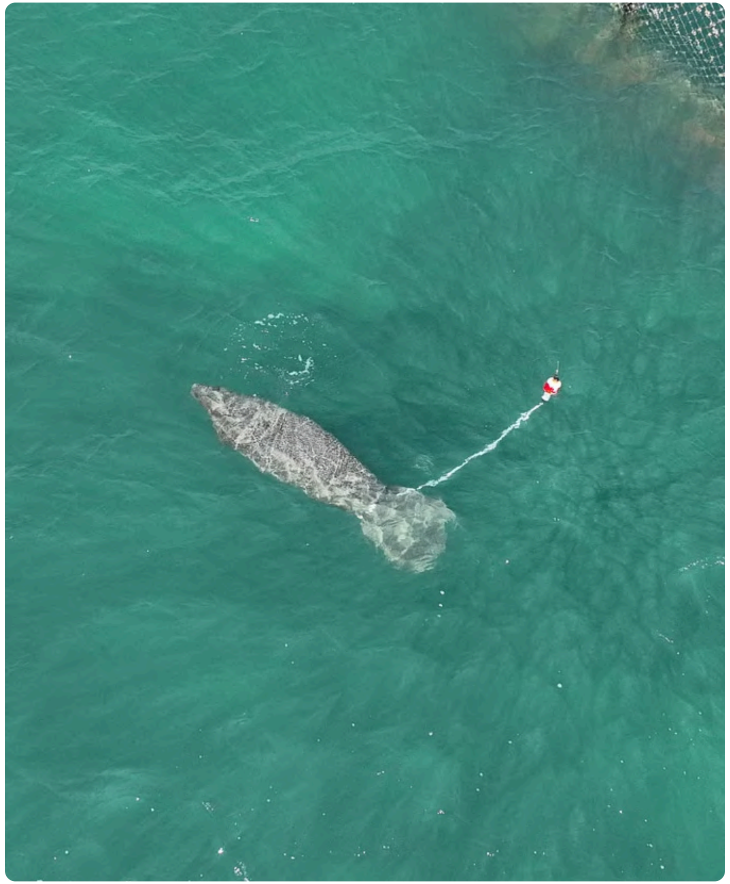
System Architecture, Hardware Modules, Connection Flow & Experiments

Practical implementation and validation approach

Satellite Communications for Constrained Devices

Overview of available technologies and fundamental trade-offs

Constrained Marine Trackers & the Satellite IoT Problem



Defining the Constraints

From an engineering point of view (device constraints):

- **Tiny devices** with strict size and weight limits (3% animal weight).
- **Severe energy budget**: small battery, sometimes energy harvesting.
- **Very low data rate**, but tolerant to **high latency**.
- **Harsh RF environment**: water, long distances, random orientation.
- **Ruggedness** in real conditions: depth/pressure, fouling, impacts, corrosion.

From a marine researcher point of view (desired tracker features):

- **Simple deployment and long duration** (years) with minimal recaptures.
- **Adequate spatial resolution** to study movement and habitat use.
- **Temporal resolution** aligned with behavior (enough points per day / per dive cycle).
- **High tag reliability**: few data gaps, graceful degradation if link is bad.
- **Animal welfare & ethics**: low drag, low weight, safe attachment, minimal disturbance.

Legacy Wildlife Telemetry Landscape

Argos System

Pioneer in satellite wildlife tracking since 1978. Robust and proven, but relatively power-hungry and requires specialized hardware with higher costs. Uses Doppler-based location derived from the satellite pass. Now evolving with the **Kinéis nanosat constellation**

Early GPS + Satellite Tags

Tag gets a **GPS fix** on the animal, then **uploads stored positions via a satellite network** (Iridium, Globalstar, etc.). Used by vendors like **Wildlife Computers, Lotek, Telonics, ATS**, offering rich tracks but at higher **cost and power**.

Other Proprietary Systems

VHF, acoustic, archival tags and hybrid solutions. Powerful in local setups, but often require **local receivers or recapture**, not global coverage.

Satellite wildlife tracker and telemetry is a mature field

Current Satellite IoT Technology Options

System / Service	Data Rate	Antenna Size	Power Use	Ecosystem / Notes
Argos / Kinéis	Low	Small/Med	Med	Long-running wildlife system; evolving with Kinéis nanosats
Iridium / Globalstar / etc	Low/Med	Small/Med	Med	Global coverage, two-way, proprietary, low-rate messaging
Myriota UltraLight	Low	Small	Low/Med	Direct-to-satellite IoT, small modules
NB-IoT over NTN	Low	Small	Low/Med	3GPP NB-IoT via satellite; players incl. AST SpaceMobile, Lynk, Sateliot, Myriota, Skylo (with partner networks)
Starlink	High	Large	Very high	Broadband IP, not for tiny tags (today)

What is 3GPP NTN?

NTN: Non-Terrestrial Networks

3GPP extensions to run LTE / NR / NB-IoT over satellites.

Same Protocol Family as Cellular

SIM/eSIM, NAS, RRC, security, and core network stay 3GPP-based.

Adapted for Space

Handles long propagation delay, Doppler effect, moving cells, device registration, and feeder links.

Two Paths

UE → Ground BS → Core → Application

UE → Satellite → Ground Gateway → Core → Application

3GPP NTN Evolution

1

Rel-15/16: Pre-NTN Groundwork

- Focus: LTE / early 5G NR
- Studies on satellite integration, channel models, and mobility challenges
- IoT specs for NB-IoT and LTE-M on terrestrial networks

2

Rel-17: First Official NTN Specs

- Formalizes NR-NTN (5G NR over satellite)
- Formalizes IoT NTN for NB-IoT and LTE-M over satellite
- Defines key aspects: delay, Doppler, timing, mobility for LEO/GEO

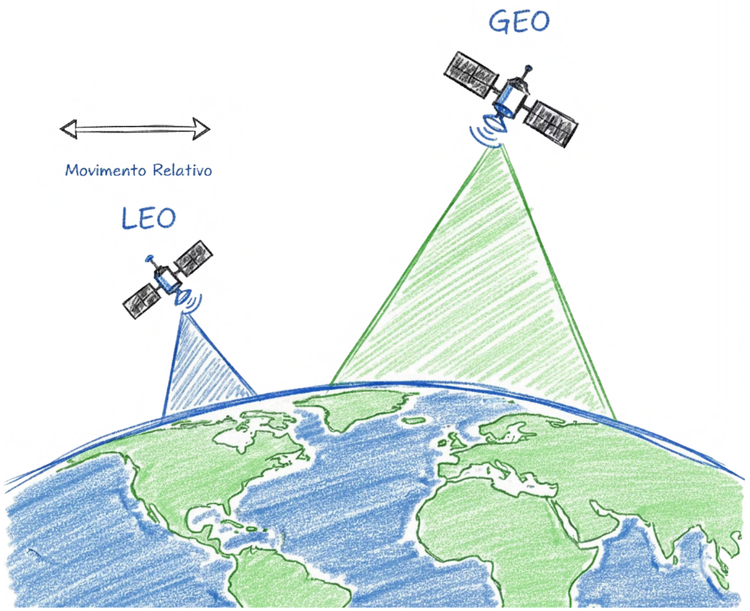
3

Rel-18+: 5G-Advanced NTN

- Enhancements to coverage, mobility, and power efficiency
- Better support for massive IoT over NTN
- Foundations for future NTN improvements for wildlife / environmental sensing

LEO vs GEO: Orbit, Coverage and Latency

	LEO	GEO
Typical Altitude	~400–1,500 km	~35,786 km
Orbital Motion	Moves quickly over Earth (orbit ~90–120 min)	Appears fixed over one point on the equator
Footprint	Small footprint, requires many satellites for coverage (~1000km)	Huge footprint, few satellites cover large areas (~15.000km)
Round-trip Latency	~30–50 ms one-way (low latency)	~250–280 ms one-way (high latency)
Implication for Tags	Short communication passes, dynamic link, lower power per hop	Continuous view, but higher link budget and latency demands



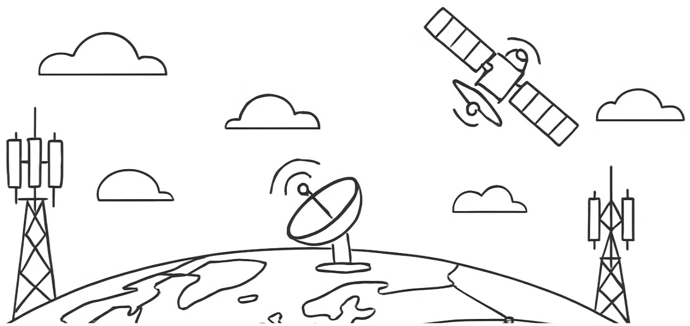
NTN Commercial & Ecosystem View

How You Buy It

- Service is usually offered via a mobile operator or aggregator.
- You use SIM/eSIM and PLMN like in terrestrial cellular IoT.
- Pricing is often message- or volume-based, typically within a cellular-style contract framework.

Why Standard NB-IoT Helps

- Multiple module vendors (e.g., Nordic, Quectel, MediaTek) share the same 3GPP stack, fostering competition and availability (not yet).
- Enables reuse of existing tools, test equipment, and security practices from terrestrial NB-IoT deployments.
- Simplifies integration into existing IoT platforms and backend stacks, reducing development complexity.



The convergence of terrestrial and non-terrestrial networks represents a significant opportunity for wildlife tracking applications.

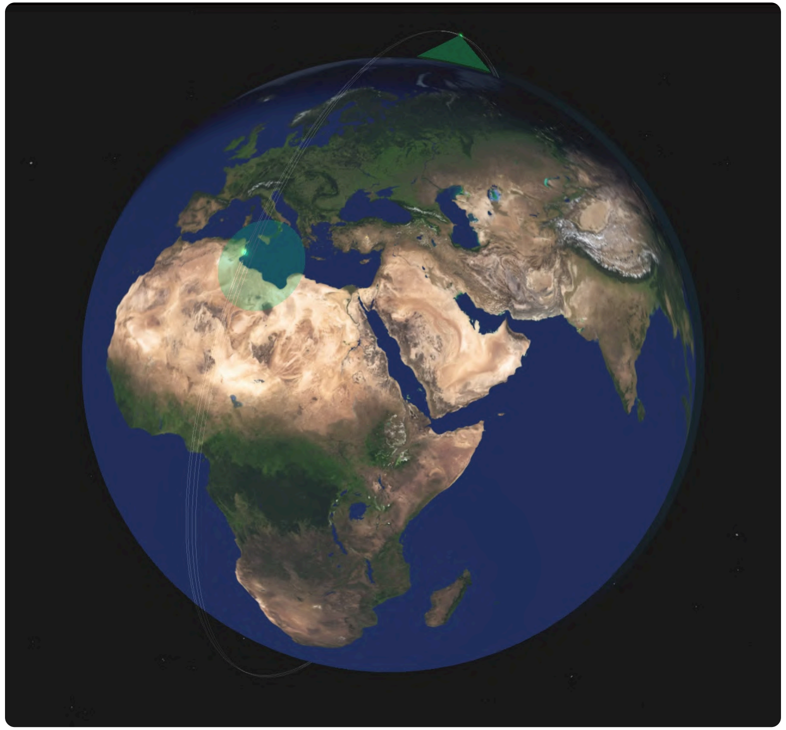
NTN Coverage & Availability Basics

- **Passes, not continuous signal:** In LEO, coverage comes as time windows with gaps in between.
- **Regulatory footprint vs RF footprint:** Where the satellite can “see” is not the same as where NB-IoT NTN is legally authorized and commercially active. Each country’s regulation and spectrum licensing defines the real service area.
- **Passes, gateways and practical availability:** pass frequency, elevation and gateway placement define how often you *actually* get usable windows for attach + uplink.
- **Module & firmware compatibility matrix**
  NB-IoT NTN support is not uniform: different modules, firmware versions and bands are compatible with different satellite providers and features (PSM, NTN mode, location services, etc.). The project must align module FW + operator profile for the specific region.

Example of Current GEO/LEO NB-NTN Coverage

Skylo (Viasat) NB-NTN Coverage in South America

https://www.groundcontrol.com/satellite-iot-networks/



Sateliot NB-NTN Coverage - 4 LEO Satellites

https://track.sateliot.com/

NAVE Project & Marine Tracking Challenge

Program objectives and why marine monitoring matters

NAVE Project Overview

Program Mission

The **NAVE** program is an innovation initiative focused on offshore and marine challenges proposed by oil & gas companies.

> **NAVE** is a program of ANP, managed by IBP and financed by energy companies.

Wildlife Tracking Challenge

Next Devices is running a project to address a Petrobras challenge on marine wildlife monitoring.

The goal is to deliver a **low-cost**, **energy-efficient** satellite tracker for marine animals (manatees first), based on NB-IoT over **NTN** and powered by **energy harvesting**.

Technology Partners

The project is led by **Next Devices**, with support from **INATEL xGMobile** (NTN/5G connectivity), **LACTEC FutureGrid** (energy harvesting), **Petrobras CENPES** (challenge owner and offshore context) and **Aquasis** (marine conservation, field operations and access to animals in captivity).

Why Low-Cost, Efficient Marine Trackers Are Critical

Source: Soltura e Monitoramento de Peixe-boi-marinho - Aquasis

The Scale Challenge

Traditional satellite tracking tags may cost thousands of dollars per unit, severely limiting the number of animals researchers can monitor simultaneously.

Scaling requirements: Comprehensive population studies need dozens to hundreds of tags deployed concurrently to generate statistically meaningful data.

Long-term operation: High energy efficiency enables years of deployment on a single battery plus energy harvesting capability, capturing seasonal cycles, migrations and rare events without frequent recapture.

Practical logistics and operations: Smart, robust trackers simplify field work, transport and installation, making tagging easier to integrate into real campaigns and routine monitoring.

Conservation impact: Lower costs and higher deployment volumes directly translate to better scientific understanding and more effective policy decisions for species protection.

Marine Environment is Brutal for RF & Energy

RF Attenuation in Water

Seawater heavily absorbs radio frequencies, making communication possible only when the tag antenna surfaces above the waterline during brief breathing events.

Unpredictable Surface Windows

Animal surfacing behavior varies by species, activity, and environmental conditions, creating short and irregular opportunities for satellite connection.

Dynamic Antenna Orientation

Waves, currents, and animal motion constantly change tag orientation, causing antenna gain patterns to vary unpredictably during critical transmission moments.

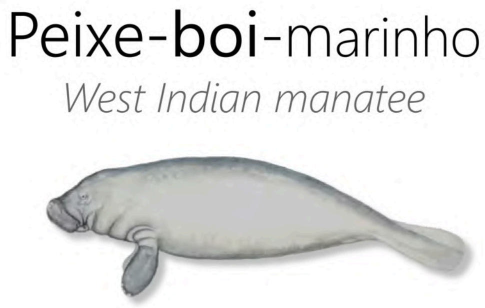
Corrosion & Biofouling

Saltwater exposure, pressure cycling, and biological growth degrade hardware performance over time, requiring robust enclosure design and materials selection.

Manatee Tracker Architecture & NTN Integration

System design from animal behavior to cloud platform

Manatee Behavior Drives Technical Requirements



Source: Peixe-boi-marinho / Biologia e Conservação no Brasil Bambu Editora e Artes Gráficas – São Paulo 2016

Biology Informs Engineering

Surfacing patterns: Manatees typically surface to breathe every 3-5 minutes during active periods, with longer intervals during rest. Each surface event lasts only seconds.

Habitat characteristics: These animals inhabit estuaries, rivers, and shallow coastal zones, often in turbid water with vegetation and varying salinity.

Derived Technical Requirements

- **Communication**: 5-15 seconds available for satellite attach and transmission, works across many hundreds of kilometers of coastline
- **Location accuracy**: 100-300 meter radius sufficient for habitat use analysis
- **Data latency**: Hours to days acceptable for most research questions
- **Operational lifetime**: Minimum 12-24 months for meaningful behavioral studies
- **Sensors**: Device diagnostic, environment and animal behavior sensors

Design Trade-offs & System Constraints

Fundamental Engineering Tensions

Power vs Reliability

Higher transmission power and more retry attempts improve link success but rapidly drain batteries

Frequency vs Antenna Size

Lower frequencies offer better propagation but require physically larger antennas

Proprietary vs Standardized

Custom protocols optimize for specific use cases while standards enable ecosystem reuse

NB-IoT over NTN doesn't magically escape these trade-offs. What we're trying to find out is: where exactly does it land for our wildlife/marine tracker, and is that position good enough to be useful for marine research at scale?

System Architecture, Hardware Modules, Connection Flow & Experiments

Practical implementation and validation approach

Marine Wildlife Tracker Hardware Architecture

MCU:

Low-power microcontroller manages sensors, schedules operations, and implements communication protocols

GNSS Receiver

Provides position fixes with configurable accuracy/power trade-offs

NB-IoT NTN Modem

Handles satellite registration, uplink transmission, and network protocols

Environmental Sensors

Temperature, depth, and activity monitoring for behavioral insights

Power Management

PMIC regulates battery discharge, potentially supplemented by energy harvesting

Antennas

Optimized GNSS and NB-IoT antennas within severe size constraints

End-to-End System Architecture

On-Animal Tracker

Integrated sensor package with GNSS, NB-IoT NTN modem, auxiliary radios, energy harvesting, battery and environmental sensors

Satellite NB-IoT NTN

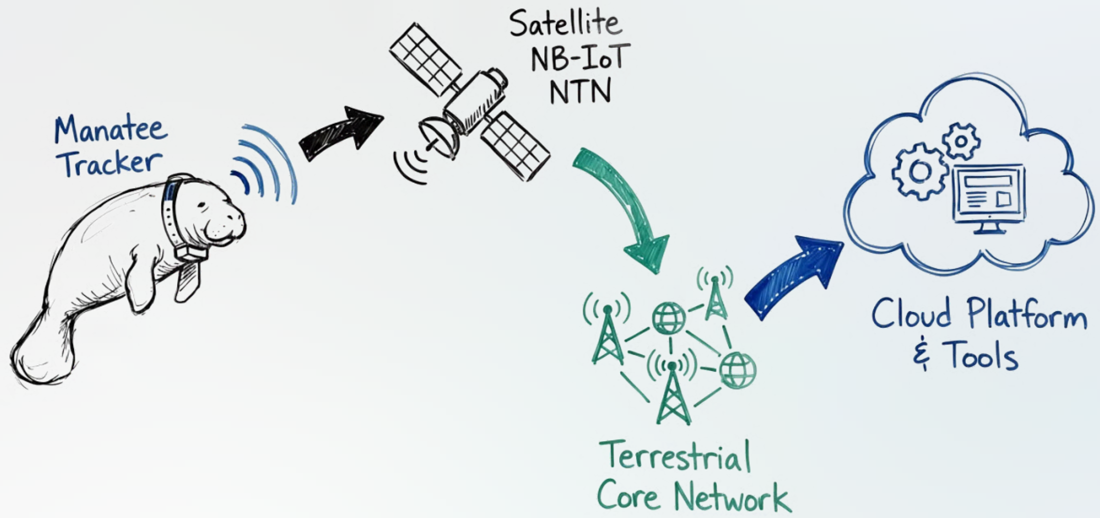
Low Earth orbit constellation providing global NB-IoT coverage via space-based base stations

Terrestrial Core Network

Ground infrastructure connecting satellite gateways to internet and application servers

Cloud Platform & Tools

Data processing, storage, visualization, and researcher access interfaces

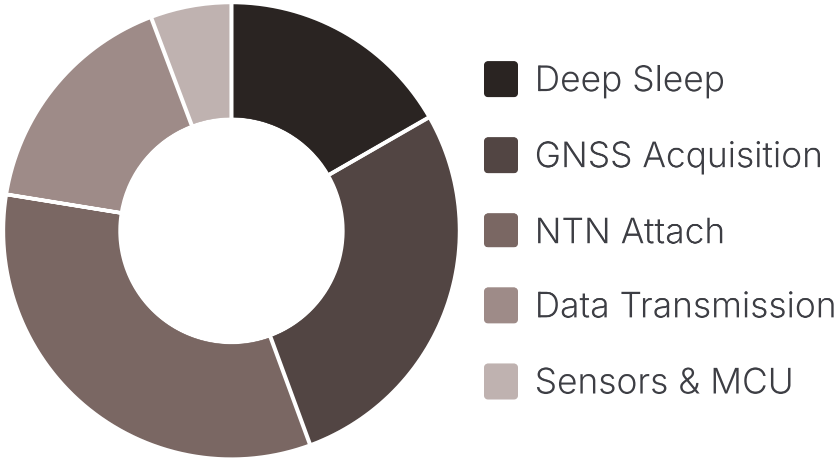


Power Budget & Energy Strategy

Lifetime Optimization Strategies

- **Aggressive duty cycling:** Tracker stays in ultra-low-power sleep between brief measurement/tx windows.
- **GNSS optimization:** Assisted GNSS is not available, fewer, well-timed fixes and reuse of last position to cut TTFF and GNSS energy.
- **NTN communication optimization:** Attach + uplink is another major energy spike. Limit attach attempts, use small/compressed payloads, and tune PSM/eDRX to minimize radio-on time.
- **Energy harvesting potential:** Solar, vibration/piezo and small hydrogenerators can trickle-charge the battery and extend lifetime.

Estimate power budget



Hardware Modules Under Test

Nordic nRF9151 A1

Module / platform: Nordic nRF9151-DK

Role in project: MCU + Modem platform for low-power NB-IoT / LTE-M with NTN support, rich tooling (SDK, power profiler, nRF Cloud)

NTN trials: Nordic is running NB-NTN / 5G-IoT trials with Sateliot's LEO constellation, achieving chip-to-cloud links using standard 3GPP NTN protocols.

Quectel BG95-S5

Module / platform: Quectel BG95-S5 Development Kit

Role in project: Modem-centric option controlled by our MCU via AT commands, used to evaluate integration, RF behavior and power profile for NB-NTN

NTN trials: Quectel's NTN modules are being certified and trialed on Skylo's satellite network (Viasat), targeting standard NB-NTN connectivity for IoT devices.

Communication & Link Strategy Over NTN

1. **Detect Surfacing Event**

   Scheduled wake-up timer or motion sensor triggers wake from deep sleep. Communication can only happen when antennas are outside the water.

2. **Acquire GNSS Position**

   Mandatory GNSS location fix

3. **NB-IoT NTN Registration**

   Network attach sequence with NTN-specific timing parameters

4. **Transmit Data Packet**

   Small uplink message containing location, sensor data, and diagnostics

5. **Return to Deep Sleep**

   Immediate shutdown to conserve battery for next cycle

Reliability vs Battery Trade-offs:

- Limit number of attempts per surfacing and per day.
- Balance message size vs frequency.
- Define fallback behavior when attach fails (backoff, skip, buffer).
- Update wake-up agenda based on battery SoC.
- Strategy may be different for LEO and GEO constellations.

Example AT Flow – Quectel BG95-S5 + Skylo NTN

Illustrative sequence for one uplink session. Exact PLMN, APN, bands and timers depend on Skylo + SIM profile and BG95-S5 FW.

timestamp	*command*	*sender*	*comment*
2025-10-24T12:20:57Z	AT	request	Basic “attention” command to verify the modem is responsive.
2025-10-24T12:21:01Z	AT+CFUN=0	request	Sets the modem to minimum functionality (RF off) to safely change network settings.
2025-10-24T12:21:11Z	AT+QCFG="nwscanmode",3,1	request	Configures network scan mode (LTE-only / NTN-focused search).
2025-10-24T12:21:13Z	AT+QCFG="band",0xf,0x8000004,0x8000004,0x2	request	Sets allowed RF bands, including the specific NB-IoT NTN band.
2025-10-24T12:21:20Z	AT+CGDCONT=1,"IP","viasat.ip"	request	Defines PDP context #1 with APN `viasat.ip` for NTN data service.
2025-10-24T12:21:21Z	AT+CFUN=1	request	Returns modem to full functionality (RF on) to start network attach.
2025-10-24T12:22:05Z	+CEREG: 1,"32DF","234B3F",14,,,,	response	EPS registration successful: module is attached to NB-IoT (NTN) network.
2025-10-24T12:22:11Z	AT+QICSGP=1,1,"viasat.ip","","",0	request	Configures data profile for PDP context 1 with APN `viasat.ip`.
2025-10-24T12:22:12Z	AT+QIACT=1	request	Activates PDP context 1 (brings up IP data session).
2025-10-24T12:22:13Z	AT+QIOPEN=1,1,"UDP","3.134.168.74",5299,0,1	request	Opens UDP socket ID 1 to server `3.134.168.74` on port 5299.
2025-10-24T12:22:13Z	AT+QISENDEX=1,"6563686f"	request	Sends UDP payload `"echo"` (hex `6563686f`) on socket 1.
2025-10-24T12:22:25Z	+QIURC: "recv",1,4,6563686F	response	UDP echo received on socket 1: 4 bytes, hex `6563686F` = `"echo"`.

Communication Timing Analysis

This analysis highlights the key timing measurements observed during the NTN experiment, showcasing the real-world performance of the AT command flow from initial modem configuration to successful UDP data echo.

Total Process Time

88 seconds (1 min 28 sec)

Measured from the very first AT command (12:20:57) to the final UDP echo response received (12:22:25).

RF Reconfiguration to Echo

84 seconds (1 min 24 sec)

This period starts from the modem's RF reconfiguration command (AT+CFUN=0 at 12:21:01) until the successful UDP echo

Network Registration to Data

20 seconds

From the moment of successful EPS network registration (+CEREG: 1 at 12:22:05) to the receipt of the UDP echo (12:22:25).

Early Experiment Objectives

Questions the Testing Program Must Answer

- What is the success probability of attach + uplink within a given time window?
- How much energy does one successful message really cost in NB-IoT over NTN, from wake-up to back-to-sleep?
- How do motion, antenna orientation and surfacing detection impact link success?
- Given a target battery and deployment duration, how many messages per day can we realistically afford?
- How close are our lab-based power-consumption estimates to what we observe in more realistic field-like tests?

What This Technology Enables

Scalable Marine Animal Monitoring

Dramatically reduced per-tag costs enable researchers to monitor larger populations simultaneously, generating more comprehensive behavioral and ecological datasets for conservation decision-making.

Reusable IoT Platform for Remote Applications

Hardware and firmware architecture extends beyond wildlife tracking to support environmental sensors, offshore equipment monitoring, and other remote IoT applications where terrestrial connectivity is unavailable.

Evidence-Based Conservation Policy

High-resolution, long-term tracking data directly informs marine protected area designation, ship traffic routing, and regulatory frameworks designed to protect vulnerable species and ecosystems.

Development Roadmap & Collaboration

1 Current Phase

Module evaluation, static testing, firmware development, and baseline performance characterization

2 6 Month Milestone

Dynamic testing completed, prototype tracker integration, initial field validation in controlled marine environments

3 12 Month Target

First on-animal deployments with manatees, tracking platform deployment, iterative design refinement based on field data

Opportunities for Collaboration

- **Marine biologists & conservation organizations:** Define research questions and deployment protocols
- **RF engineers & antenna designers:** Optimize link performance under motion and environmental constraints
- **Data scientists:** Develop analytics and visualization tools for behavioral insights
- **Satellite network operators and MVNOs:** Negotiate service terms and optimize network parameters
- **Funding agencies:** Support scaled deployments and long-term monitoring programs

Lessons from Early NTN Experiments

Uncertainty about connectivity costs and commercial agreements.

Uncertainty about interoperability between modules and NTN operators.

Few LEO satellites in current constellations, limiting coverage and availability.

Sub-optimal Viasat GEO position/elevation for Brazil’s coastal area, partial coverage

Hard to obtain hardware and test SIMs for experiments
(should improve after December)

Thank You

Questions?

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Technical Deep Dive: PSM & eDRX in NTN Context

Power Saving Mode (PSM)

PSM allows the tag modem to enter a deep sleep state while remaining registered with the network, waking only for scheduled transmission windows.

NTN considerations: Satellite movement means the same cell may not be available when the tag wakes. Firmware must handle cell reselection gracefully without full reattachment overhead.

Timer configuration: Active timer (T3324) and periodic TAU timer (T3412) must balance network paging requirements with battery conservation goals.

Extended Discontinuous Reception (eDRX)

eDRX extends the paging cycle length, allowing the modem to remain asleep for longer intervals between downlink monitoring opportunities.

Wildlife tracking trade-off: Most tracking applications require only uplink capability, making aggressive eDRX configuration or PSM without downlink monitoring attractive for maximum battery life.

Latency implications: Extended sleep cycles mean commands or configuration updates from the cloud may experience delays measured in hours or days.

Current Satellite IoT Technology Options

A diverse array of satellite IoT options exists, each with unique characteristics catering to different applications. Understanding these differences is crucial for selecting the optimal solution for wildlife tracking.

Argos / Kinéis	LEO, **25 nanosats** in 5 polar planes	**UL:** UHF around **401 MHz** (401.58–401.61 MHz for telecommand) **DL:** UHF ~400 MHz (Argos legacy also used ~465–468 MHz)	Proprietary Argos/Kinéis waveform	Wildlife tracking, ocean buoys, environmental telemetry
Iridium	LEO, **66 active sats + spares**	**UL/DL:** L-band **1616–1626.5 MHz**	Proprietary, TDMA/FDMA over L-band	Global tracking, M2M, safety services, SBD / Certus IoT
Globalstar	LEO, ~**24–25 operational sats** in second-gen constellation	**UL:** L-band **1610–1618.725 MHz DL:** S-band **2483.5–2500 MHz**	Proprietary; bent-pipe MSS	Asset tracking, SPOT, iPhone Emergency SOS, low-rate data
ORBCOMM	LEO, ~**30 sats**	**UL:** VHF **148–150 MHz DL:** VHF **137–138 MHz**	Proprietary packet system	Logistics, containers, industrial M2M
Inmarsat / Viasat – IsatData Pro	GEO, **4–5+ L-band sats** for classic MSS / IDP	**UL:** L-band around **1626.5–1675 MHz** (return channel) **DL:** L-band around **1525–1559 MHz**	Proprietary narrowband MSS	Remote SCADA, oil & gas, maritime, industrial M2M
Myriota (UltraLite / HyperPulse)	LEO, **40+ nanosats** in partnership with Spire; targeting ~50+	**UL:** VHF (Service 1) around **148–150 MHz DL:** UHF around **400–450 MHz** (both services use UHF downlink)	Proprietary IoT waveform + new 5G NTN-aligned service	Ultra-low-power IoT, long-life battery nodes in remote areas
Astrocast	LEO, **~18–20 sats** in orbit; plan ~80 total	**UL/DL:** L-band (~1.6 GHz MSS allocations; details not all public, but positioned as L-band IoT network)	Proprietary satellite IoT	Industrial/remote monitoring, asset tracking
Lacuna Space (LoRa from space)	LEO, **small but growing constellation** (single-digit/low-teens sats)	**UL:** ISM sub-GHz **862–870 MHz** (EU) or **902–928 MHz** (US) from LoRa/LoRaWAN devices **DL:** sub-GHz UHF (LoRaWAN downlink)	LoRa / LoRaWAN direct-to-satellite	Extending existing LoRaWAN stacks to global coverage
EchoStar Mobile – LoRa NTN	GEO, **EchoStar XXI S-band GEO sat** (plus future LEO S-band plans)	**UL/DL:** S-band around **2 GHz** (licensed MSS S-band for sat link), plus sub-GHz ISM for local LoRa in dual-mode modules	LoRa / LoRaWAN over GEO S-band	Pan-European LoRa IoT where terrestrial LoRaWAN can't reach
Skylo (NB-IoT NTN over partner sats)	Uses **Viasat/Inmarsat L-band GEO constellation + other MSS sats** – so "virtual" constellation over multiple GEOs	Devices certified for **B23 (2 GHz MSS), n255 (L-band), n256 (S-band)** → roughly **L-band ~1.6 GHz** and **S-band ~2.0 GHz** UL/DL	3GPP **NB-IoT NTN** (Rel-17)	Standard NB-IoT modules with satellite roaming (sensor/asset data, SMS-like traffic)
Sateliot (5G NB-IoT NTN)	LEO nanosats; **network planned at 100–250+ sats; a handful currently in orbit**	Target **3GPP bands n255 (L-band) & n256 (S-band)**; example: **n256 FDD 1980–2010 MHz UL / 2170–2200 MHz DL** in 2 GHz MSS band	3GPP **5G NB-IoT NTN**	Direct NB-IoT connectivity for standard chips via MNO roaming
OQ Technology (5G NB-IoT LEO)	LEO; **growing from 3 to ~10+ sats**, targeting "world's largest 5G NB-IoT LEO operator"	Uses **MSS L- and S-bands** aligned to 3GPP NTN (e.g., n255 L-band ≈1.6 GHz, n256 S-band ≈2.0 GHz UL/DL)	3GPP **NB-IoT NTN**	Narrowband 5G IoT, direct-to-device and hybrid cell+satellite coverage
Starlink (broadband)	LEO, **~8,800 working sats; >10,000 launched**, target >12k (phase 1) and up to 34k	**User UL:** mainly Ku/Ka **~14–14.5 GHz** (and Ka up to ~30 GHz) **DL:** Ku-band **~10.7–12.7 GHz**; gateways also use Ka/E-band	IP broadband (standard or "Business")	Backhaul for IoT gateways (LoRa, BLE, Wi-Fi, etc.), high-throughput sites
Starlink Direct-to-Cell	Same LEO constellation, with dedicated **LTE/NTN payloads** on newer sats	**UL/DL:** 3GPP LTE bands in sub-GHz (e.g., 700–900 MHz, depends on partner MNO spectrum) plus work to share 1.6/2.4 GHz MSS bands with Globalstar in future	Standard LTE (Rel-17 D2D/NTN direction)	Direct-to-phone SMS, voice/data; future low-rate IoT, plus gateway/backhaul use

This table summarizes key characteristics of leading satellite IoT providers, highlighting differences in orbit, link bands, interface standards, and typical use cases. It illustrates the growing landscape of NTN options for various applications.

Packet Flow: LEO vs GEO, Transparent vs Regenerative

LEO (Low Earth Orbit)

Satellites move quickly, short passes

GEO (Geostationary Orbit)

Satellites appear fixed, continuous visibility

Transparent Payload

Satellite acts as a simple relay

LEO Transparent

UE → LEO Sat (moving) → Ground Gateway + BS → Core

- Frequent handover
- Lower latency, short visibility, not practical

GEO Transparent

UE → GEO Sat (fixed) → Gateway + BS → Core

- Very high latency
- Tough link budget for tags

Regenerative Payload

Satellite processes and routes traffic

LEO Regenerative

UE → LEO Sat (onboard BS) → Gateway (IP) → Core

- Satellite handles Doppler, MAC
- Still requires handover

GEO Regenerative

UE → GEO Sat (onboard BS) → Gateway (IP) → Core

- High latency, simpler ground side
- Complex satellite network

Metrics, Logging & Analysis Framework

Key Performance Indicators

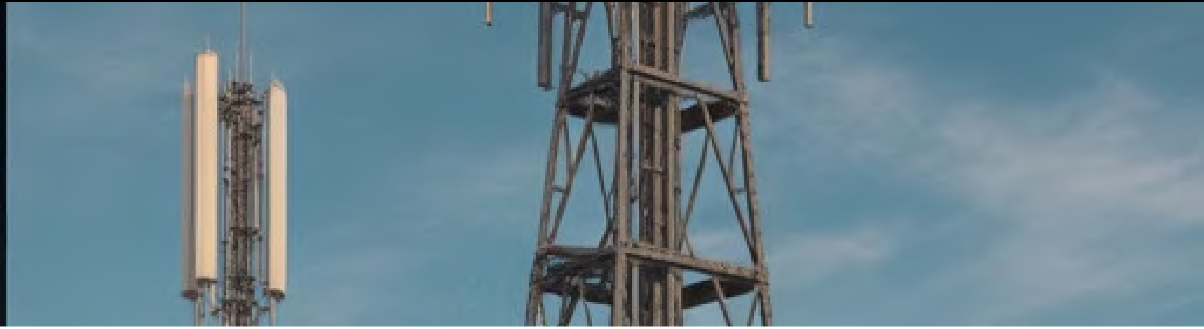
Metric Category	Parameters Captured
Timing Data	Timestamps, attach duration, GNSS TTFF
Radio Quality	RSRP, SNR, RSRQ, cell ID
Connection Success	Attach outcomes, RA attempts, retries
Energy Consumption	Current profiles, charge per operation
Position Data	GNSS coordinates, accuracy estimates
Environmental	Temperature, motion, orientation

Informing Design Decisions

Collected metrics directly drive critical design parameter selection:

- **Minimum surfacing time**
  Determine required surface duration for acceptable attach success rates
- **Daily message budget**
  Calculate sustainable transmission frequency given battery capacity
- **Retry strategy**
  Optimize retry attempts vs energy expenditure trade-off
- **Battery sizing**
  Project realistic operational lifetime under field conditions

This data-driven approach ensures design choices align with empirical performance rather than theoretical assumptions.



Developer Gotchas: NTN vs Terrestrial NB-IoT

Propagation Delay Impact

Longer round-trip time to the satellite forces more relaxed timers and retry settings than in terrestrial NB-IoT.

Moving Satellites and Sparse Coverage

LEO cells come and go with each pass, so usable coverage is time-dependent and not continuous..

Antenna & Sky View Critical

Waves, tilt and partial submersion constantly change antenna gain and line-of-sight, making the link margin fluctuate.

Robust State Machines Required

Firmware must gracefully handle extended offline periods, attach failures, and unpredictable network availability with comprehensive logging for debugging.

Intermittent communication windows

Long dives plus gaps between satellite passes create extended periods with effectively zero chance to communicate.

Store-and-forward latency

Even after a successful uplink, delivery to the backend can be delayed by the satellite's buffer and feeder-link availability.