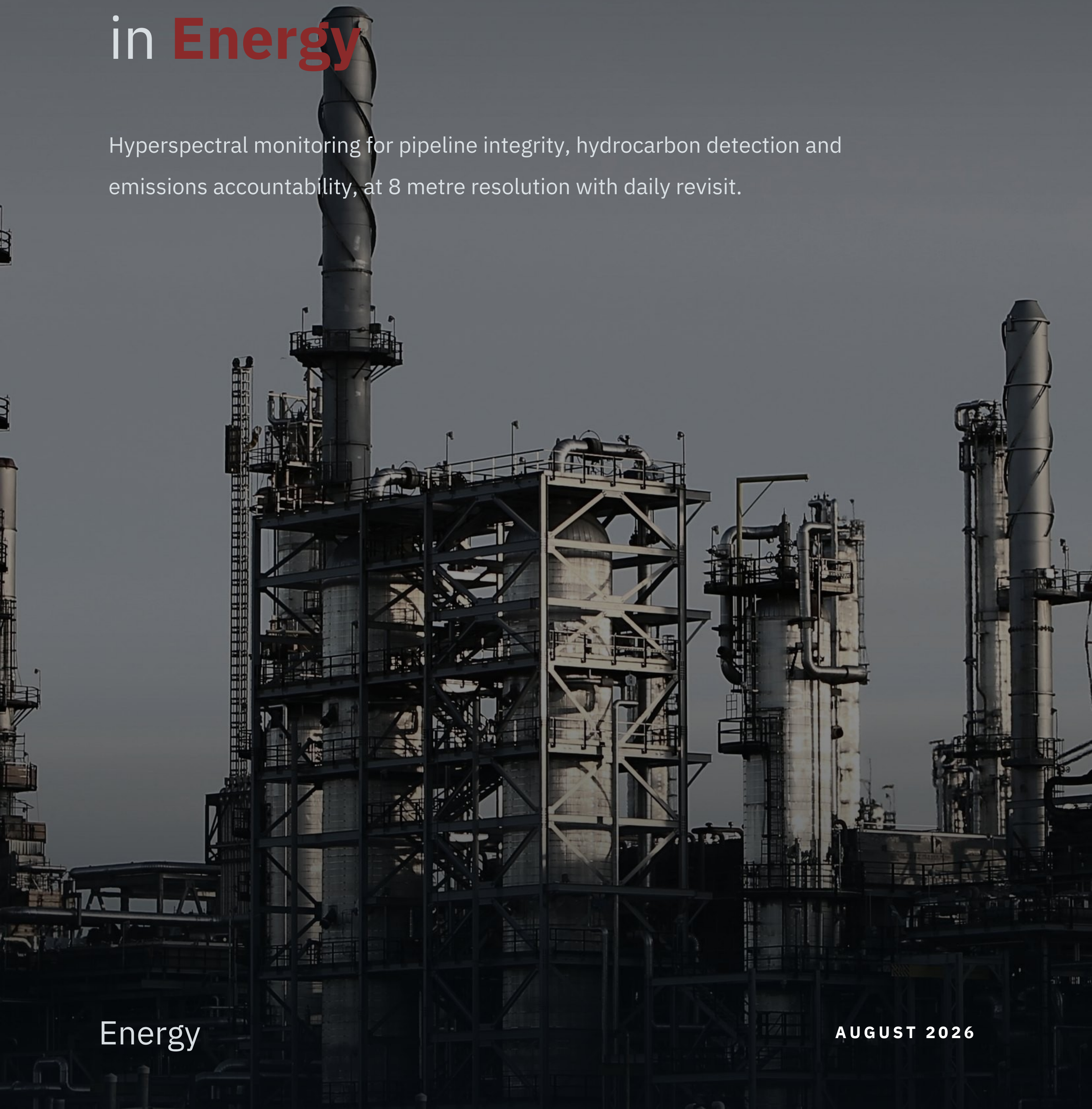
axine

The Spectral Advantage in Energy

Hyperspectral monitoring for pipeline integrity, hydrocarbon detection and emissions accountability, at 8 metre resolution with daily revisit.



Energy

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Contents

Introduction

This paper sets out how hyperspectral imaging supports the energy sector, and how Axine Laboratories applies satellite spectroscopy to pipeline right-of-way monitoring, hydrocarbon detection, emissions accountability and site environmental management. It is written for integrity engineers, HSE and sustainability leads, and asset managers evaluating where space-based monitoring fits alongside aerial survey and ground inspection.

Gathering lines running into a processing facility. Linear assets are the natural unit for a monitoring product: a buffered corridor, differenced from one acquisition to the next.

Motivation: monitoring obligations are outrunning survey capacity

The scale of the assets requiring surveillance is the starting point. The onshore United States pipeline network alone runs to roughly 3.3 million miles of pipe carrying natural gas, crude oil and other hazardous liquids[1], much of it crossing ground that is remote, seasonally inaccessible, or both. Every mile of that network carries an integrity management obligation, and the conventional means of discharging it are aerial patrol, ground walkover and fixed instrumentation, each of which trades coverage against cost.

Third-party excavation remains among the most persistent threats to that network. Since 2005 there have been more than 875 excavation-related pipeline incidents in the United States, resulting in 40 fatalities, 166 serious injuries and approximately 322 million US dollars in property damage. In 2025 alone, operators recorded 85,606 excavation damages to gas distribution facilities across 35.8 million excavation tickets[2]. These are events that begin as visible surface disturbance days or weeks before they become incidents.

On emissions, the regulatory position has changed faster than most monitoring programmes. The International Energy Agency estimates methane emissions from oil, gas and coal operations at 124 million tonnes a year, with oil the largest single source at 45 Mt, and finds that the fossil fuel sector accounts for around 35 per cent of methane emissions from human activity[3]. Nearly 30 Mt of upstream oil and gas emissions could be abated at no net cost under 2025 energy prices, and the IEA calculates that acting on satellite-detected large emission events within recommended timelines would alone have cut global oil and gas emissions by around 6 Mt in 2025[3].

Regulation has followed. The EU Methane Regulation entered into force in August 2024, and from 1 January 2027 importers must demonstrate that oil, gas and coal entering the Union was produced under monitoring, reporting and verification measures equivalent to those applied to EU operators, or meeting OGMP 2.0 Level 5 with third-party verification[4]. The readiness gap is substantial: roughly seven per cent of global oil and gas production reported at OGMP 2.0 Level 5 in 2024, against forecasts of around twenty-six per cent by 2027[5]. Measurement-based, independently verifiable emissions data has moved from a reputational asset to a condition of market access.

Satellite hyperspectral imaging addresses both problems with the same instrument. It measures surface and atmospheric composition directly, over entire corridors and basins, on a cadence set by orbital revisit rather than by crew availability.

What is hyperspectral imaging?

Every material interacts with light in a way determined by its chemistry. Hydrocarbons absorb in the short-wave infrared through the vibrational modes of carbon-hydrogen bonds, producing diagnostic features near 1700 and 2300 nanometres. Methane absorbs in the same broad region through its own vibrational transitions. Nitrogen dioxide absorbs in the blue and green. Vegetation under stress shifts the position of its red edge before any change is visible to the eye. Each of these is a spectral signature, and each identifies a substance or a condition rather than merely recording a colour.

Conventional imagery cannot resolve those features. An RGB sensor records three broad bands. A multispectral sensor records between four and twenty, each tens of nanometres wide. Hyperspectral sensors divide the spectrum into hundreds of contiguous narrow bands, each typically under 10 nm, producing a complete spectrum for every pixel in the scene.

A comparison of RGB, multispectral and hyperspectral imagery.

Type	Number of bands	Bandwidth (FWHM)	Wavelength range
RGB	3	~50-70 nm	450-700 nm
Multispectral	4-20	~15-35 nm	400-2350 nm, discontinuous
Hyperspectral	100-500+	Under 10 nm	400-2500 nm, contiguous

The consequence for energy applications is specificity. A multispectral index can tell an operator that vegetation along a corridor is less vigorous than it was last quarter. A hyperspectral measurement can distinguish drought stress from hydrocarbon-induced stress, because the two produce different spectral responses. A broadband sensor can show that a water surface has changed appearance. A hyperspectral sensor can measure the carbon-hydrogen absorption that identifies the change as petroleum.

The tasked acquisition tier

For operational monitoring, Axine acquires imagery from a commercial hyperspectral constellation of six identical microsatellites offering:

- 472 contiguous spectral bands across the full visible to short-wave infrared range, 400 to 2500 nm, covering the complete hydrocarbon and gas absorption region.
- 8 metre ground sample distance in the hyperspectral channels, the finest commercially available hyperspectral resolution currently in orbit.

+ 3 metre panchromatic imagery co-acquired for spatial context and feature identification.
+ Revisit of up to daily for most locations worldwide, with directed tasking over a defined corridor or facility.

Resolution is what converts spectral capability into an operational product for linear infrastructure. A right of way is typically tens of metres wide. At 30 or 60 metre ground sampling the corridor and its surroundings fall into the same pixel and are averaged together. At 8 metres the corridor is resolved across its width, and a single excavator working within it occupies a measurable fraction of a pixel rather than a negligible one.

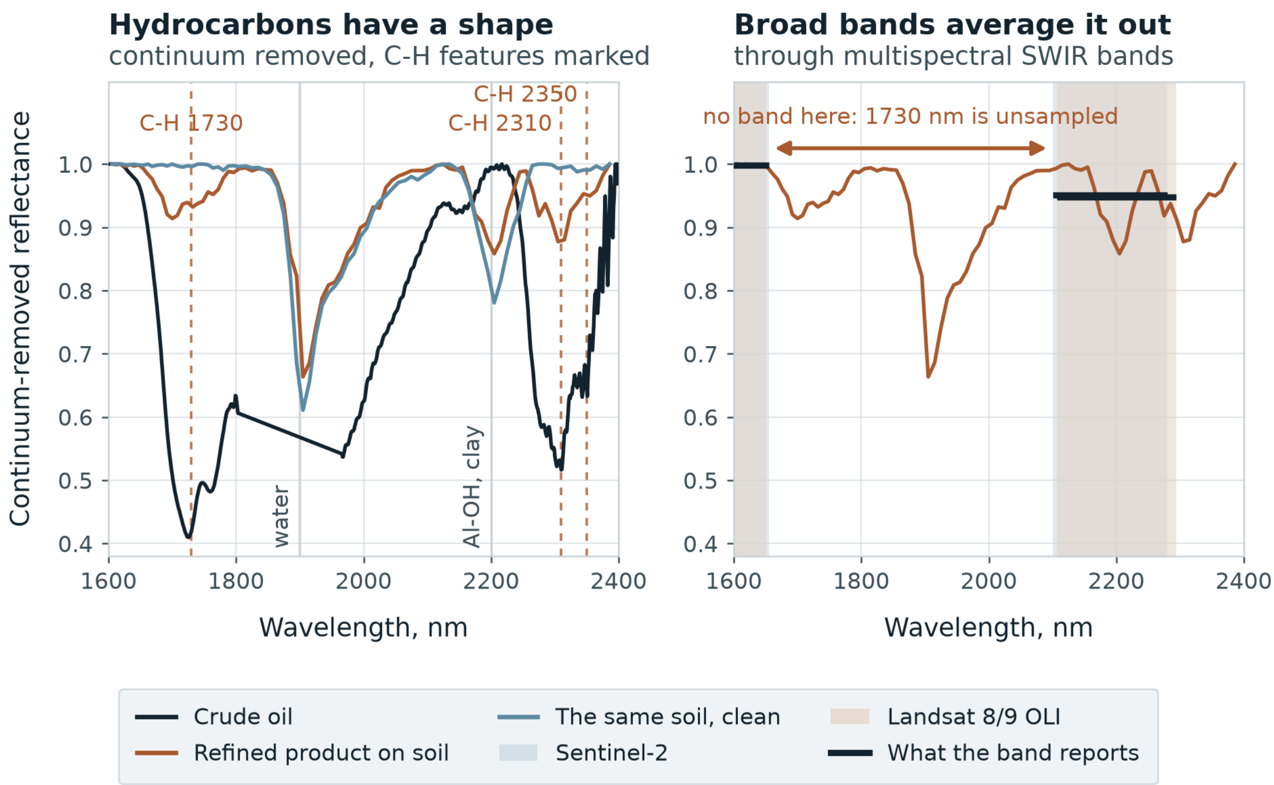

Figure 1 — Crude oil, refined product on soil and the same soil clean, continuum removed across 1600 to 2400 nm. The carbon-hydrogen features near 1730, 2310 and 2350 nm are what identify a hydrocarbon. On the right the same spectrum read through broadband sensors: 1730 nm is not sampled at all, and what the bands report is a flat line.

Challenges in the energy sector

Energy operators are being asked to monitor more assets, to a higher evidentiary standard, across a wider set of environmental parameters, without a proportionate increase in survey budget. The constraints below are the ones satellite spectroscopy is well positioned to relieve.

A transmission corridor at dusk with trees standing close to the conductors. Encroachment on a right of way is a change-detection problem long before it becomes an inspection problem.

+ **Coverage against cost:** Networks span thousands of kilometres across terrain that is remote, seasonally inaccessible or politically sensitive. Aerial patrol and ground walkover deliver high-quality observation over a small fraction of the asset at any moment, and the interval between passes is where risk accumulates.
+ **Detecting threats before they become incidents:** Excavation damage, encroachment and unauthorised construction all begin as visible surface change. The operational question is not whether the change is detectable but whether anyone is looking at that kilometre on the day it appears.
+ **From estimates to measurement:** Emissions reporting is moving from engineering estimates and emission factors to measurement-based, source-level, independently verified data. Frameworks including OGMP 2.0, the EU Methane Regulation and national greenhouse gas reporting programmes all point the same direction.
+ **Early detection of contamination:** Contamination discovered late is remediated at multiples of the cost of contamination discovered early, and the regulatory and reputational consequences scale with the delay. Spectral evidence of soil hydrocarbons appears well before visible symptoms.

- **Environmental baselines and closure:** Operators are increasingly required to demonstrate the condition of land, water and vegetation around their assets, before, during and after operations, with time-stamped evidence rather than assertion.
- **Fragmented monitoring programmes:** Sites are surveyed for methane, for hydrocarbons, for vegetation condition and for water quality by separate contractors on separate schedules with separate reporting formats. A single instrument that addresses several of these produces a coherent record rather than a filing cabinet.
- **Social and stakeholder expectations:** Community and investor scrutiny of energy projects now extends to land use, water and livelihood impacts. Transparent, independently derived monitoring data supports engagement in a way that internal reporting does not.

Hyperspectral imagery in action

Across the energy value chain, hyperspectral imagery supports three fundamental capabilities.

- **Detection:** Identifying the presence of hydrocarbons on soil and water, gas plumes in the atmospheric column, surface disturbance within a corridor, and stress in vegetation, across the full extent of a scene.
- **Classification:** Distinguishing between substances and between causes: crude from refined product, hydrocarbon-induced vegetation stress from drought, authorised ground works from unauthorised excavation.
- **Quantification:** Measuring plume extent, contamination footprint, corridor encroachment and change between acquisitions, producing quantities that can be tracked, reported and audited.

The table below sets out the spectral regions relevant to energy operations, the parameters diagnosed in each, and their operational significance.

Diagnostic spectral regions and their significance for energy operations.

Band group	Wavelength (nm)	Parameter	Significance
Blue to green	420-610	Nitrogen dioxide	Air quality and industrial emission monitoring
Green	560-590	Ethane	Flare performance and gas leak indication
Green to red	508-880	Oil slick on water	Spill identification, extent and emulsion state
VNIR	400-1000	Water quality parameters	Produced water, impoundment and receiving water monitoring
Red edge	690-730	Vegetation stress	Early indication of subsurface leakage and corridor condition
NIR	750-900	Canopy vigour, biodiversity	Right-of-way vegetation state and habitat baseline
SWIR	1550-1750	Soil moisture, canopy water	Fuel load and dry vegetation near flammable-product lines
SWIR	1690-1790	Soil-adsorbed hydrocarbons	Petroleum contamination in soil
SWIR	1650, 2200-2400	Methane	Greenhouse gas and leak

Band group	Wavelength (nm)	Parameter	Significance
			detection
SWIR	2000-2400	Surface composition along corridors	Right-of-way integrity and disturbance mapping
SWIR	2308-2349	Crude oil	Product type discrimination and source attribution

Axine layers are released progressively and each carries an explicit validation posture, described in section 8. Feature positions are given as ranges because exact positions vary with composition, concentration and surface conditions.

Counted on the 60 m measurement, before any smoothing: 2,935 pixels (16.1% of 18,254 valid) clear three sigma on the long features alone, and only 194 (1.06%) also clear it at 1730 nm. Carbonate absorbs at 2340 nm and not at 1730 nm, and here the two long features correlate at +0.886 with each other but only +0.333 with the specific one. A single-layer map would call 17% of this site hydrocarbon; corroboration leaves 1%. The 10 m detail is an edge guide from the optical image, not spectral resolution.

Figure 2 — *A port and tank farm in true colour, beside carbon-hydrogen corroboration confidence over the same ground. Requiring the 1730 nm feature to agree with the longer ones takes the flagged area from 17 per cent of the site to 1 per cent: most of what a single-feature map would call hydrocarbon is carbonate.*

Hyperspectral versus multispectral imaging in energy

Multispectral imagery remains valuable for context, land cover and coarse change detection. Hyperspectral imagery answers a different class of question, because chemical identification requires bands narrower than the absorption features themselves.

Parameter	Multispectral imaging	Hyperspectral imaging
Hydrocarbon detection	Visible slicks and gross staining	Carbon-hydrogen absorption measured directly on soil and water
Product discrimination	Not resolvable	Crude and refined products separated by spectral contrast
Gas detection	Not resolvable	Methane and ethane absorption features accessible in the SWIR
Vegetation stress	General vigour indices	Stress cause differentiated through narrowband pigment and water indices
Corridor encroachment	Coarse land cover change	Species and condition change resolved within the right of way
Water quality	Turbidity and gross colour	Specific constituents separated by pigment and absorption features
Spatial detail	10-30 m typical	8 m, with 3 m panchromatic context
Revisit	Fixed orbital schedule	Directed tasking, up to daily for most locations
Change monitoring	Disturbance extent	Compositional change between acquisitions

The distinction is a matter of physics rather than vendor preference: chemical identification requires narrow contiguous bands, and narrow contiguous bands are what defines a hyperspectral sensor.

The Axine analytical method

Axine runs a deterministic, physics-based detection layer. Substances are identified by measuring absorption features against measured reference spectra rather than by a trained classifier inferring a label. The result is an output that is reproducible, sensor agnostic, and traceable to a measured feature at every pixel, which is what makes it suitable as evidence rather than merely as indication.

Reflectance, radiance and masking

Imagery is ingested from any supported sensor and reduced to the product level each analysis requires. Surface detection works on reflectance; atmospheric gas detection works on radiance, because a plume modifies the light path rather than the ground. Cloud, shadow and unmeasurable ground are screened and reported explicitly as not evaluated, so every flagged pixel represents a measurement.

Continuum removal and absolute band depth

Each spectral window is continuum removed so that absorption features are measured independently of overall brightness and slope, and features are quantified as absolute band depths. This is materially more reliable on mixed pixels than comparing whole-spectrum shapes, which matters on corridors where a single pixel may contain soil, vegetation and infrastructure.

Iterative residual pursuit

Real pixels contain mixtures. Once a component is fitted, its modelled contribution is removed and the residual is searched again, resolving multiple co-occurring components per spectral window. On an energy asset this is the difference between reporting that a pixel contains something absorbing in the SWIR and reporting what is present alongside what.

Per-pixel noise floor

Detection thresholds derive from the radiometric uncertainty of the specific sensor at the specific wavelength, computed per pixel from instrument characteristics. Thresholds set from physics rather than tuned to a desired outcome are what make a detection on one asset comparable to a detection on another, and what makes a time series meaningful.

Change detection and corridor logic

Repeat acquisitions are differenced against a baseline within a buffered corridor or facility boundary supplied by the operator. Detections are classified by threat type, located, assigned a severity, and delivered with the imagery evidence attached, so that an alert arrives as a reviewable case rather than as a coordinate.

Plume detection and rate estimation

Atmospheric gas plumes are detected by matched filtering against the target gas absorption, mapped for extent, and attributed to a source. Emission rate follows from integrated mass enhancement combined with a wind field, and is reported as a range conditioned on wind and surface conditions rather than as a single unqualified figure, which is how the measurement is actually constrained.

Use cases across the asset lifecycle

A generating site from the air. One acquisition puts the whole footprint on a single dataset and a single date — buildings, laydown, hardstanding, the vegetation margin and the river beyond it.

Pipeline and linear infrastructure integrity

+ **Encroachment monitoring:** Vegetation density, vigour and species change tracked within a buffered right of way against a baseline, identifying growth that threatens access, inspection sightlines or the pipe itself.
+ **Excavation and construction detection:** Land cover and surface disturbance change detection along the corridor, surfacing new ground works, access tracks, spoil heaps and structures that were not there at the previous pass.
+ **Dry fuel load assessment:** Canopy and soil water content mapped through SWIR moisture indices, identifying accumulations of dry vegetation adjacent to flammable-product lines.
+ **Natural hazard exposure:** Erosion, washout, slope disturbance and soil moisture anomaly mapped along the route, supporting geohazard zoning and prioritisation of ground inspection.
+ **Leak-indicative vegetation stress:** Localised vegetation stress inconsistent with the surrounding drought and phenology signal, one of the earliest surface expressions of subsurface product loss.

Hydrocarbon detection and spill response

+ **Soil-adsorbed hydrocarbons:** Carbon-hydrogen absorption measured in the 1690 to 1790 nm region, mapping contamination extent across a facility, a corridor or a legacy site without ground sampling.
+ **Slicks on water:** Slick extent mapped across inland and coastal water, supporting response prioritisation and post-event documentation.

+ **Product type discrimination:** Spectral contrast in the 2308 to 2349 nm region supporting differentiation of crude from refined product, which bears directly on source attribution.
+ **Remediation tracking:** Repeat acquisition over a remediation footprint, tracking contraction of the contaminated area over time as objective evidence of remedial progress.

Emissions monitoring and compliance

+ **Methane plume detection:** Plume extent mapped and attributed to a source, with rate estimated from integrated mass enhancement and wind, reported with an explicit uncertainty range.
+ **Flare and vent monitoring:** Ethane absorption in the green region supporting assessment of flare performance and unlit or inefficient combustion.
+ **Verification of reported data:** Independent, satellite-derived observations to complement operator-reported data, supporting the measurement-based reconciliation that OGMP 2.0 Level 5 and the EU Methane Regulation both require.
+ **Compliance reporting:** Detections and time series compiled into audit artefacts aligned to named reporting regimes, generated from the same evidence base the analysis was performed on.

Site, water and environmental management

+ **Water quality:** Constituent-specific monitoring of produced water ponds, tailings and impoundments, and of receiving water bodies downstream of operations.
+ **Pre-operational baseline:** Vegetation, soil surface composition and water condition documented before construction, providing an objective reference against which later change is measured.
+ **Renewable siting support:** Surface reflectance, soil stability and terrain roughness characterised across candidate sites for solar and wind development, and across storage and grid infrastructure locations.

Decommissioning and closure

+ **Rehabilitation monitoring:** Revegetation progress, soil surface recovery and residual disturbance tracked against the pre-operational baseline and packaged as a periodic report suitable for regulatory submission.
+ **Closure evidence:** Time-stamped, repeatable evidence of surface condition across a closed site, generated without site access and without contractor mobilisation.

Validation and confidence

Axine treats validation as a product feature. Every analytical layer carries a stated validation posture, and every performance figure we publish is traceable to a documented test against an independent reference.

Validation posture on every layer

Each layer in the platform renders with an explicit posture: calibrated region, validated region, or screening. Deterministic band mathematics quotes no accuracy figure because none is claimed for it. Fitted and learned products quote accuracy where they have been tested against ground truth for that region, and ship as screening elsewhere with the reason stated. An operator always knows which of the three they are looking at, which is what makes an Axine layer safe to place in front of a regulator or a board.

Protocol

+ **Pre-registration:** Test design, thresholds and success criteria are fixed and recorded before evaluation data is examined.
+ **Frozen parameters:** Detection parameters derive from instrument characteristics and are not adjusted after results are seen.
+ **Hash-sealed inputs:** Input imagery and reference libraries are hashed, so any published result can be reproduced against the exact data that produced it.
+ **Stability testing:** Leave-one-region-out and single-site-removal runs confirm that reported performance is not carried by any single site.
+ **Leakage controls:** Label permutation runs confirm that measured performance collapses when labels are destroyed, the standard test for information leakage.
+ **Append-only logging:** Every comparison run is written to an append-only log, providing a complete audit trail behind any figure we quote.

Reference data

For gas quantification, controlled-release experiments are the reference standard, and several public controlled-release datasets exist against which detection limit and rate accuracy can be characterised as a function of wind speed and surface albedo. For surface hydrocarbons, verified contamination footprints and sampling records provide the equivalent. Axine secures reference data alongside development rather than after it, because a detection layer without a documented reference is an indication rather than a measurement, and our clients are increasingly required to file the latter.

Reporting practice

Performance is reported as full confusion matrices with Cohen’s kappa and balanced accuracy, or as intervals rather than point estimates, with the validation regime named alongside. On the mineral products where this discipline is longest established, Axine publishes comparisons against independent United States Geological Survey reference products, and quotes ranking performance as an area under the ROC curve of 0.7465 with a 95 per cent credible interval of 0.663 to 0.819 under spatially blocked validation. The same reporting standard governs every vertical.

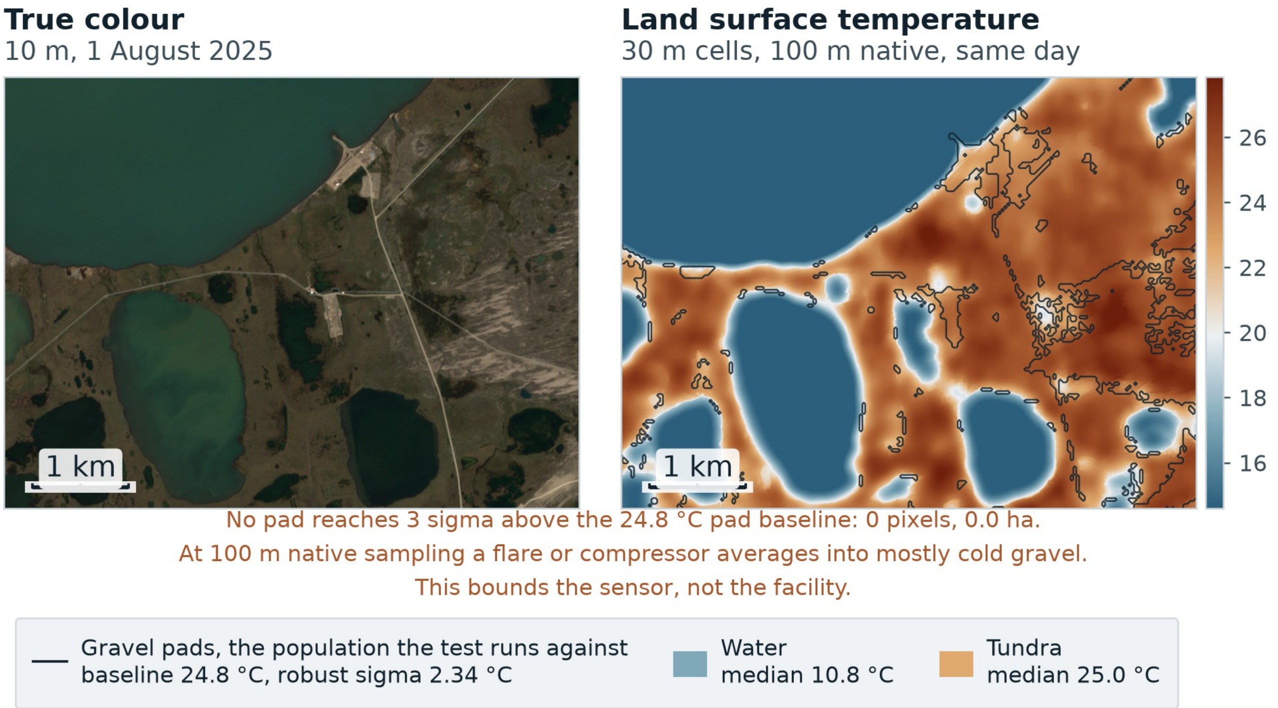

Figure 3 — *Gravel pads on the North Slope in true colour, beside land surface temperature for the same day. No pad clears three sigma above the 24.8 °C pad baseline — at 100 m native sampling a flare or compressor averages into cold gravel. The figure is published because it bounds the sensor, not the facility.*

Operational benefits

+ **Coverage at asset scale:** A single acquisition covers an entire corridor or basin, converting a sampling problem into a census. Directed tasking sets the cadence to the risk rather than to the flight schedule.
+ **Early detection:** Encroachment, disturbance and contamination are surfaced while they are still surface change rather than after they have become incidents, which is where the cost differential in integrity management sits.
+ **Evidence-grade output:** Every detection traces to a measured absorption feature and a named reference spectrum, inspectable pixel by pixel and reproducible on demand, which is what a regulator, an insurer or an auditor actually requires.
+ **One instrument, several obligations:** Methane, hydrocarbons, vegetation condition and water quality derived from the same acquisition, replacing several separately contracted survey programmes with one coherent record.
+ **Personnel and access risk:** Remote monitoring reduces the need to place personnel on remote, hazardous or politically sensitive ground, and requires no field installation.
+ **Predictable economics:** Everything derived from public satellite data is free, permanently. Tasked acquisition is priced per square kilometre against a defined area of interest, so programme cost is known before commitment.
+ **Data sovereignty:** Areas of interest, corridor geometries and results remain within Axine infrastructure and are never transmitted to a third-party model provider.

A generating station on the waterfront. Plume, thermal signature, site condition and the receiving water are all surface measurements that one repeat acquisition can carry at once.

Inherent product properties

Stacks and cooling towers across open farmland. Reflectance spectroscopy reads the surface it can see, so the ground around an asset forms as much of the record as the asset itself.

+ **Complete spectral coverage:** Contiguous narrow-band coverage from 400 to 2500 nm captures the full diagnostic range for hydrocarbons and hydrocarbon gases, including the carbon-hydrogen features above 2300 nm that shorter-range sensors cannot reach.
+ **Chemical specificity:** Substances identified against measured reference spectra, allowing crude to be separated from refined product and hydrocarbon stress to be separated from drought.
+ **Resolution matched to linear assets:** 8 metre hyperspectral ground sampling with 3 metre panchromatic context, resolving corridor-scale features that regional imagery averages into background.
+ **Monitoring cadence:** Revisit of up to daily for most locations, turning a static survey into a monitored time series with alerting between epochs.
+ **Deterministic and reproducible:** A physics-based detection layer produces the same answer on the same data every time, with no dependence on training data resembling the asset under observation.
+ **Sensor agnostic:** One pipeline ingests public archive sources and tasked high-resolution imagery, so results remain comparable as a programme moves between tiers.
+ **Analysis-ready delivery:** Cloud-optimised GeoTIFF outputs, API access and generated reports designed to enter an existing GIS, integrity management system or reporting workflow.

Optimal operating conditions

Optical spectroscopy measures the illuminated surface and the atmospheric column above it, so the method performs best in daylight, cloud-free conditions over exposed ground, water, infrastructure and managed corridors. Screened ground is reported as not evaluated rather than inferred. Gas rate quantification is conditioned on wind field and surface albedo and is quoted as a range on those terms, which is how the measurement is physically constrained and how it should be reported to a regulator.

Platform, access and data handling

A distribution substation. Fixed sites are small enough to sit inside a single frame and repetitive enough that change between acquisitions, rather than any one image, carries the information.

The platform

Work is ordered and delivered through a web application. Users define an area of interest or upload a corridor geometry, search available imagery or request a tasked acquisition, and follow the order through a staged job queue. Results are served as cloud-optimised GeoTIFFs with map tiling, and any pixel can be opened to inspect its full spectrum, the features measured, and the reference spectra those features were fitted against. Monitoring subscriptions run the same analysis on a schedule and raise alerts against a baseline. Results are catalogued, reports are generated as PDF, and workspaces support teams, roles and notifications. An API is available for clients working in their own GIS or integrity management environment.

Lisa

Lisa is a client-facing assistant that runs entirely on Axine infrastructure rather than on a third-party model service. She searches imagery, estimates pricing, retrieves results, saves and lists areas of interest, geocodes, and reports the current model version with its validation metrics. Order submission is confirmation-gated by design, and any request requiring judgement is escalated to a human analyst.

Self-hosting is a procurement decision rather than an engineering preference. Corridor geometries and facility locations are operationally sensitive, and they never leave Axine infrastructure.

Access tiers

Tier	Coverage
Free	Everything derived from public satellite data, including screening layers, visualisation, Lisa and API access. Axine does not charge for information obtained freely.
Tasked	Directed 8 metre hyperspectral acquisition over a defined corridor or facility, with full analysis, priced per square kilometre against a stated minimum area.
Monitoring	Scheduled repeat acquisition with change detection, alerting and reporting between epochs, on volume terms.

About Axine Laboratories

Axine Laboratories builds commercial hyperspectral analytics for the energy, mining, agriculture and water monitoring sectors. The company is registered in the United States and run by a technical team of geologists and engineers.

Our approach rests on three commitments. Detection is physics-based and reproducible, fitted against measured reference spectra rather than inferred by an untraceable model. Every published figure is backed by a pre-registered test against an independent reference, with the validation regime stated alongside it. And analysis derived from public satellite data is free and will remain so, because we do not charge for information obtained freely.

Revenue comes from tasked high-resolution acquisition and the analysis performed on it, which aligns our interest with delivering observations a client could not otherwise obtain rather than with metering access to imagery that is already public.

Axine Laboratories

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2. Pipeline and Hazardous Materials Safety Administration. Advisory Bulletin on Preventing Excavation Damage During National Safe Digging Month and Beyond, Docket PHMSA-2026-1585, April 2026. Over 875 excavation-related pipeline incidents since 2005 with 40 fatalities, 166 serious injuries and approximately 322 million US dollars in property damage; 85,606 excavation damages to gas distribution facilities across 35,813,977 excavation tickets in 2025.

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