TECHNOLOGY BRIEF

From Mars to Markets: LIBS is Defining the Next Industrial Era–Will You Lead or Lag?

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This report is for those shaping the future of industry—researchers, engineers, business leaders, and strategists—the ones making smarter, faster, data-driven decisions. LIBS has transformed space exploration, yet its adoption on Earth has been slower. Not because it lacks potential, but because real change requires more than technology—it needs economic value, integration, and proof. This is a guide to where LIBS is making an impact, why it matters now, and how those who embrace it will stay ahead.

INTRODUCTION – BREAKING THE LAB LOCK

Rovers on Mars classify rocks instantly with laser pulses. On Earth, industry waits weeks for the same data. This stark reality—not science fiction—is laser-induced breakdown spectroscopy (LIBS). This technology has saved NASA hundreds of millions while most industries still ship samples to far-off laboratories.

The gap defies logic: traditional analysis methods are too slow, too complex, and too far from decision points. Staff collects samples, mails them elsewhere, and waits weeks for results stripped of their original context. This lab lag was tolerable in the past. Today, it is a competitive liability costing billions in delays and missed opportunities.

The solution is proven: LIBS eliminates the lab lag. A single laser pulse instantly reveals elemental composition—from hydrogen to uranium—collapsing the decision cycle from weeks to seconds.

The proof exists: in mineral exploration, agriculture, manufacturing, and environmental monitoring, purpose-built LIBS systems now deliver results faster and more precisely than the laboratory techniques they're replacing.

Companies across mining, process control, field instrumentation, and next-generation sensing are creating undeniable returns on investment. Early adopters are achieving precision that matches or exceeds laboratory methods, and unlocking entirely new sense-and-act capabilities like real-time carbon capture verification.

The future trajectory is clear. As instrument costs fall and AI integration accelerates, LIBS adoption will follow the familiar path from specialized tool to industry standard to ubiquitous technology. Industries that wait will find themselves at a decisive disadvantage to competitors operating with real-time intelligence at the source.

This report examines LIBS' evolution from scientific curiosity to mission-critical technology, the economic and cultural imperatives driving adoption, and the compelling financial case for implementation now—not later.

The question isn't whether LIBS will transform industry—it's whether you'll be among the first to benefit.

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STATUS QUO – SLOW, COSTLY, AND HOLDING INDUSTRY BACK

The Crushing Cost of Delayed Analysis

The phone rings at an iron mine in northern Minnesota. The mine geologist's face tightens as she listens. The crusher operators, 20 miles down the rail tracks, are furious. The ore grade has shifted, forcing them to halt operations and recalibrate kit—a process that will take hours and cost over $500,000 in lost production.

"This happens several times a year," she admits. Her only method for determining what grade is being sent downstream: handpick samples, ship them to a laboratory hundreds of miles away, and wait four weeks for results. By then, her team has blasted another area, loaded another train, and another potential shutdown looms.

Iron crushers at this and other operations run at just 40% efficiency partly due to these disruptions. The opportunity cost: hundreds of millions yearly from a single plant. The solution—instant elemental analysis—exists. It operates daily on Mars. Yet here on Earth, mine operations remain chemically blind.

Extreme Environments, Extreme Inefficiency

Local miners describe their ultimate altitude-induced headache at 5,000 meters in the Chilean Andes, where the air is thin and progress is slow. A single 450-point survey costs $100,000 and takes three months. In this rarefied world, mules are the only transport, carrying the weight of both equipment and time.

When shown NASA's plans to explore Saturn's moon Titan—using hopper drones that analyze surface composition at each landing point—they looked like they'd struck ore. The same coverage could be achieved in ten days—a 30-fold reduction in time. The math is clear: faster surveys, immediate geochemical mapping, and less environmental impact and safety risks (*1*).

But mining still sinks time and money into slow, manual sampling—sending people into hazardous terrain for data that should already be in hand.

Agriculture's Blind Spots

Farmers face a similar data drought. At $200 per sample, soil testing is economically viable only every two acres, every other year. This lack of data forces agronomists to apply fertilizer in broad strokes—overloading some areas while leaving others deprived.

The financial penalty is severe. Growers typically spend $200 per acre on nitrogen fertilizer for corn. Inefficiencies from imprecise application add approximately 30% to these costs—$60 per acre that directly erodes farm profitability. For an industry operating on tight margins, this represents the difference between profit and loss, all because critical soil data arrives too infrequently and too late.

The environmental cost compounds the financial waste: excess fertilizer contributes to greenhouse gas emissions and creates runoff that contaminates waterways.

Why It Matters

These inefficiencies were tolerable decades ago. They are not tolerable now; the lab lag jeopardizes climate targets. Lithium faces an 84% deficit by 2030. Cobalt shortage reaches 63%. The Nickel gap hits 53% (*2*). When exploration campaigns require four-week waits between sampling and analysis, a single site assessment stretches to 7-10 years. This analytical jam alone makes climate goals mathematically impossible. No amount of funding or political will can overcome physics: batteries, turbines, and solar panels require minerals that cannot be found at necessary rates when geologists operate blindfolded by laboratory delays.

The high cost of soil testing creates a data gap that undermines food security. According to UN calculations, agriculture must grow by 70% by 2050. Yet productivity growth has slumped to 1.16% annually since 1990—far below the 2.12% during the tractor and chemical revolution (*3*). Because soil testing is too expensive, agronomists rely on sparse, infrequent sampling. They apply too much fertilizer in some areas and not enough in others. The result: compromised yields, water pollution, and avoidable emissions—all from decisions made with incomplete data.

Manufacturing suffers identical analytical paralysis. Real-time emissions control requires real-time compositional data. Circular economy efforts collapse without immediate material identification. Carbon capture verification demands instant elemental analysis to validate storage. In each case, waiting weeks for laboratory results doesn't just increase costs—it makes regulatory compliance and sustainability targets functionally unattainable. Industries cannot optimize what they cannot measure when they need to.

The True Cost of the Lab Lag

The laboratory chokepoint extracts an enormous toll from industry. Direct costs include sample collection, preparation, shipping, and analysis fees—often $200-500 per sample. For large operations running thousands of samples annually, this represents millions in explicit spending.

Operational costs emerge from decisions delayed or made with insufficient information. These include production inefficiencies (like the crusher example), resource misallocation (as in agriculture), and exploration delays (as in prospecting).

Yet for all these penalties, the greatest cost is opportunity lost. Mineral deposits remain undiscovered. Agricultural yields fall short of potential. Manufacturing processes operate below optimal efficiency. Carbon sequestration goes unverified and unmonetized.

Combined, these inefficiencies potentially amount to hundreds of billions of dollars annually—an invisible tax long accepted as inevitable.

Companies that close the lab lag gain immediate efficiency, resource utilization, and market speed advantages. The solution exists now—it's delivering instant data on Mars, 140 million miles away. If real-time analysis works, why do outdated laboratory methods persist wherever time-to-data matters?

LIBS – ELEMENTAL TRUTHS

"Send sample to lab. Wait. Analyze. Wait. Report results. Wait." This mantra has governed chemical analysis for a century. LIBS shatters that paradigm with atomic elegance, turning wait-and-see into sense-and-act.

A single laser pulse strikes matter, instantly heating it to temperatures rivaling the sun's surface. In this flash of energy, material transforms into plasma—a state where atoms break apart completely. As this miniature star cools, electrons fall back into place, emitting precise wavelengths of light unique to each element. Within microseconds, a spectrometer reads these spectral fingerprints, revealing a material's entire elemental makeup (*4*).

The process requires no chemicals, no sample preparation, and produces no waste. It works on solids, liquids, powders, and even molten metal. And it happens in real time, at the point of decision, rather than weeks later in a distant laboratory. This is not a marginal improvement on existing methods. It is a fundamental reimagining of elemental analysis.

Consider the alternatives. X-ray fluorescence (XRF) fails to detect critical light elements like hydrogen, lithium, and carbon. Inductively coupled plasma (ICP) techniques demand extensive sample preparation—dissolving solids in acid, creating new delays and hazards. Infrared spectroscopy measures molecular bonds rather than elemental composition directly. Each method brings compromises in speed, comprehensiveness, or accessibility.

LIBS eliminates these trade-offs entirely. With a single pulse, it detects every element, from hydrogen to uranium, providing instant compositional analysis wherever decisions are made. The implications extend far beyond convenience.

When analysis shifts from weeks to seconds, entire business models transform. Mineral exploration campaigns that once progressed at glacial pace now adapt their strategy daily. Manufacturing quality control transitions from statistical sampling to 100% inspection. Agricultural inputs move from broad application to precision placement. Carbon capture verification becomes continuous rather than intermittent.

These capabilities create competitive divides that will define industries for decades. Companies harnessing real-time elemental data will optimize resources, minimize waste, and turn bigger profits. Those relying on traditional methods will increasingly resemble competitors who once insisted that digital cameras would never replace film.

The technology's components are deceptively simple: a pulsed laser creates the plasma, collection optics gather the emitted light, a spectrometer separates wavelengths, and sophisticated software identifies elemental signatures. Recent advances in each area have transformed LIBS from laboratory curiosity to industrial workhorse (*5*).

Today's LIBS systems range from handheld devices to fully automated industrial installations. They operate in environments from Arctic ice to molten metal, from nuclear facilities to agricultural fields. The technology has matured from

Box 1: LIBS at a Glance.

LIBS measures every element in the periodic table in milliseconds—no proxies, no chemical reagents, no waiting. Just direct, real-time elemental analysis. Simple in principle, but achieving this precision took centuries of scientific progress.

It all starts with atoms—the ancient idea that all matter is made of indivisible particles. In 1917, Einstein's theory of stimulated emission laid the foundation for lasers. By 1960, scientists had built the first pulsed ruby laser and noticed something remarkable: when focused on a material, it created a glowing plasma that revealed its elemental makeup. A new way to analyze matter was born.

For decades the technology remained largely confined to research settings—showing promise but lacking practical implementation. David Cremers and Leon Radziemski at Los Alamos National Laboratory saw the practical potential. In the 1980s, they refined the laser parameters and detection methods, transforming LIBS into a reliable tool. Their work, documented in the *Handbook of Laser-Induced Breakdown Spectroscopy*, remains fundamental to the field. Since then, LIBS has moved beyond the lab and into industries worldwide.

- **How it works:** A laser pulse creates plasma; as it cools, the plasma emits element-specific light, which a spectrometer analyzes
- **Detection range:** Every element in the periodic table
- **Analysis time:** 1–50 milliseconds per measurement
- **Sample preparation:** None. LIBS works directly on solids, liquids, and gases
- **Measurement distance:** From contact to over 15 meters
- **Applications:** Mining, agriculture, manufacturing, recycling, nuclear, defense, security, pharmaceuticals, forensics, food safety, art restoration, biomedical diagnostics, carbon capture, space exploration, and environmental monitoring

LIBS has been used to find gold in ore, measure contaminants in drinking water, detect explosives, authenticate historical artifacts, monitor greenhouse gases, analyze slurries, and even explore the deep-sea. Its reach is expanding, limited only by our imagination.

experimental to industrial, from specialist domain to everyday tool.

The economics are equally compelling. While each traditional laboratory analysis costs $200-500, LIBS measurements incur effectively zero marginal cost after initial investment. A mining operation previously limited to 1,000 samples monthly by budget constraints can now perform thousands daily, creating unprecedented insight granularity. More significantly, LIBS eliminates the opportunity costs of delayed decisions—the true expense of traditional methods.

LIBS represents a clear technological inflection point. Just as digital imaging transformed photography, real-time elemental analysis will reset expectations across industries. The question is not whether businesses will adopt LIBS but when—and at what competitive cost to those who delay.

The technology was so compelling that even NASA, perhaps the most risk-averse organization when it comes to unproven technology, took a giant leap: LIBS would be the cornerstone of Mars exploration. That bet would prove transformative for planetary science—and chart a clear course for industries still adrift in analytical fog.

MARS PROOF – WHERE FAILURE ISN'T AN OPTION

"In God we trust. All others, bring data"—the mantra framed at NASA's Johnson Space Center captures its stance on new kit. A single failure can mean billions lost, years of delays, and congressional inquiries.

That's why NASA's choice to fly LIBS on two flagship Mars missions is so remarkable.

From Gamble to Mission-Critical

In 2012, NASA's Curiosity rover landed on Mars carrying ChemCam—a first-of-its-kind LIBS system designed to analyze Martian rocks from a distance. The decision to include this unproven technology was not made lightly (*6*). ChemCam had to work alongside gold-standard instruments like X-ray diffraction and mass spectrometry, techniques trusted for over a century.

The risk was significant. Curiosity costs around $200,000 per day to operate (*7*). If ChemCam failed, one of the rover's key instruments would be dead weight—a costly mistake NASA could ill afford.

Instead, ChemCam transformed Mars exploration. For the first time, scientists could analyze rocks without physical contact: no driving, no sample collection, no contact measurements. Just point, shoot a laser, and receive elemental data in seconds. ChemCam has fired over three million laser shots on Mars, analyzing hundreds of targets and producing a geochemical map of Gale Crater unlike anything previously possible.

If the science broke new ground, the financial return shattered cost models. Each full sample analysis using Curiosity's internal laboratory takes six to eight days—burning $1.2 million in rover time. This ability to rapidly screen targets has prevented at least 20 unnecessary full analyses annually, saving well over $200 million in mission resources since deployment. An instrument that cost roughly $50 million to develop has paid for itself multiple times over.

Doubling Down on LIBS

NASA's second bet came in 2021. Perseverance, the newest Mars rover, carries SuperCam—an evolution of the LIBS technology that combines laser spectroscopy with multiple other sensing modalities. This time, NASA made an even bolder move: they eliminated the onboard laboratory equipment that had defined previous missions.

The shift was deliberate. SuperCam now serves as the primary geochemical screener, determining which rare samples are valuable enough to be cached for eventual return to Earth. With each returned sample projected to cost approximately $250 million (*8*), SuperCam's ability to identify the most scientifically valuable targets represents billions in potential savings.

This isn't merely a case study in technology adoption. It's evidence of a fundamental shift in approach. NASA abandoned century-old methods in favor of LIBS when it mattered most (*9*). The once-experimental technology is now trusted to guide billion-dollar missions millions of miles from Earth.

Box 2: The Mars Journey: A Firsthand Perspective.

My involvement with LIBS spans two decades, from early experimental systems to mission-critical deployments on Mars. While at the Canadian Space Agency, I worked directly with ChemCam data, developing machine learning techniques to process the overwhelming volume of spectral information streaming back from Mars—work that earned one of the first patents in AI-driven spectral analysis.

The challenge was unprecedented: ChemCam produced more geochemical data in its first month than all previous Mars missions combined. Traditional analysis methods couldn't keep pace. My solution—kernel partial least squares regression—enabled real-time quantitative analysis with minimal calibration, correcting for atmospheric influence and matrix effects—how different materials absorb, scatter, and emit light in complex ways. This experience shaped my understanding of what LIBS could achieve beyond space exploration. I witnessed firsthand how instant, non-contact elemental analysis transformed decision-making—not just in scientific terms, but in operational efficiency. Later, my work combining LIBS with Raman spectroscopy for remote sensing set distance records analyzing Arctic icebergs. These techniques directly influenced SuperCam's design on Perseverance, where we now use LIBS alongside complementary spectroscopic methods.

The pattern is clear: what works millions of miles away on Mars works even better on Earth. Industries facing analytical bottlenecks are discovering what NASA proved a decade ago—LIBS delivers actionable intelligence when and where it matters most.

From Mars to Industry

NASA faced the same problem confronting industries today: traditional analysis methods were too slow, too complex, and too sample-intensive. Their solution—LIBS—delivered real-time elemental data without sample preparation or laboratory delays. While NASA took years to validate LIBS for mission-critical applications, today's implementations benefit from that decade of proven performance.

FROM SPACE TO INDUSTRY – WHAT WORKS ON MARS WORKS ANYWHERE

While NASA was firing lasers at Martian rocks, a handful of companies were quietly solving a more prosaic challenge: making LIBS work in factories, mines, and foundries. Their stories reveal both the technology's industrial potential and the stubborn barriers that have kept it from widespread adoption.

Adapting LIBS to Industry's Demands

Canada's National Research Council spotted LIBS' potential for mining two decades ago when its researchers demonstrated gold detection in laboratory settings. Yet practical deployment remained stubbornly elusive. Elemission, founded by an NRC researcher, eventually bridged this gap by transforming experimental prototypes into systems robust enough for mineral analysis. Their trajectory illustrates the first industrial LIBS challenge: delivering national laboratory-grade precision in the real world. Their high-performance systems now serve sophisticated mining operations and research institutions—though at premium prices that keep them from becoming everyday tools.

The challenge of environment came next. Britain's Applied Photonics emerged from a critical problem in nuclear energy: how to analyze aging reactor components without dismantling them. Their solution—fiber-optic LIBS probes—brought analysis to places too hazardous for humans. Unlike competitors pursuing standardization, Applied Photonics embraced customization. Their modular systems now analyze underwater pipelines, detect explosives for defense agencies, and inspect infrastructure that standard instruments cannot reach. Their approach treats LIBS not as a product but as a solution framework for extreme analytical environments.

Integration into production workflows represented another frontier. Germany's Laser Analytical Systems & Automation (LSA) approached LIBS from the production engineer's perspective when it spun off from the Fraunhofer Institute in 2004. Rather than developing laboratory instruments, they created systems that operate continuously above conveyor belts in recycling centers and processing plants. Their key breakthrough was maintaining analytical precision while materials move at several meters per second—transforming LIBS from a batch process to a continuous one. Their work on the EU-funded ReSoURCE initiative now points toward a future where real-time elemental analysis enables truly circular manufacturing.

Perhaps the greatest industrial barrier was usability. America's Energy Research Company (ERCo) tackled this by simplifying LIBS for one of industry's most unforgiving environments: molten metal production. Their in-situ systems monitor aluminum composition during smelting, replacing dangerous manual sampling with instantaneous analysis. Their focus on single-button operation and automatic calibration eliminated the need for analytical expertise—a crucial step toward making LIBS practical for everyday industrial use.

The Inertia Problem

These four approaches—precision, adaptation, integration, and simplification—have collectively transformed LIBS from scientific curiosity to industrial tool. Yet none has achieved the mainstream adoption their innovations deserve. The gap between capability and implementation remains substantial, even as the underlying technology continues to mature (*10*).

Why? Because the real barriers to LIBS adoption aren't technical but institutional. Industries build rituals around laboratory cycles. Quality protocols name specific tests rather than performance standards. Managers defend familiar methods like territory. Most crucially, the separation of sampling from analysis—embedded in workflows for decades—makes real-time measurement seem almost heretical.

Breaking through these barriers requires more than technical improvement. It demands a comprehensive approach that addresses technological performance, economic justification, and cultural adaptation simultaneously. While the pioneers described here have built impressive technology, they've largely failed to solve the implementation puzzle.

The next act in this industrial saga comes from an unexpected direction. A company forged in Mars exploration has begun weaponizing targeted applications against these institutional barriers—with results that may finally bring the lessons of space exploration down to Earth.

IMPOSSIBLE SENSING – RETHINKING LIBS

The technology that conquered Mars stalled on Earth for a simple reason: nobody asked what customers actually needed. LIBS has long been dominated by technical pioneers—brilliant minds advancing the hardware but often overlooking the realities of adoption. At Impossible Sensing, we took a counterintuitive approach.

That meant looking where others don't, because breakthroughs don't happen where everyone is already searching. Real change comes from what's overlooked and dismissed. We also understood that no transformative idea is ever proven in advance. Demand proof too soon, and you kill it. That left only one path forward: pursue solutions that seem irrational at first—or, as Arthur C. Clarke put it, venturing a little way past the limits of the possible. And it works: we deliver LIBS results that used to be science fiction.

Soil Mapping: Precision at Scale

Precision agriculture promises efficiency, but the reality for most farmers remains blunt-force fertilization. Conventional soil testing is slow, expensive, and far too sparse to guide decisions at

Box 3: Breaking Barriers—What Holds LIBS Back?

After two decades championing LIBS, I've heard every concern—from lab techs to executives. These aren't just objections; they're real hurdles that have slowed adoption. Some are misconceptions, others are valid—but all have solutions. These barriers aren't unique to LIBS. New technologies aren't rejected because they're not better. They're rejected because they're new. But history shows that when a technology delivers faster, cheaper, and better results, adoption is inevitable. LIBS is no exception—it's just a matter of when.

1. **"Matrix effects kill it"**
   Surface variability can throw off results, but calibration-free techniques and data fusion solve this. The science is solid; industry adoption just needs to catch up.
2. **"It's not quantitative"**
   LIBS isn't XRF or ICP-MS, but its massive data stream enables robust statistical modeling. In some cases, LIBS-based models already outperform traditional lab methods.
3. **"Hardware isn't rugged enough"**
   LIBS works on Mars, but Earth is rougher—literally. That's why industrial LIBS is built to withstand real-world abuse, from mining trucks to factory floors.
4. **"Software isn't user-friendly"**
   True, most analytical software isn't. LIBS needs better interfaces that serve users, not demand expertise. The industry is moving toward more intuitive, AI-driven tools.
5. **"Requires calibration and maintenance"**
   Legacy instruments had drift issues. Modern LIBS is far more stable, but old perceptions linger.
6. **"Can't measure what I need"**
   A Catch-22—without adoption, there's no proof; without proof, no adoption. The only fix? Real-world success stories.
7. **"It's not safe"**
   LIBS lasers aren't toys, but neither are industrial tools. Proper safeguards and training eliminate risk, just like in any workplace.
8. **"Too expensive"**
   Everyone wants NASA-grade tech—until it comes with a price tag. But LIBS costs a fraction of ICP-MS, and in many applications, the ROI speaks for itself. The perception of cost is often the bigger barrier than the actual cost.
9. **"No clear ROI"**
   That one's on us—LIBS providers. If we can't quantify the cost savings, efficiency gains, and waste reduction, we can't expect companies to take the leap. Clear financial metrics make adoption a business decision, not a technical gamble.
10. **"My competitors don't use it, why should I?"**
    Another Catch-22. Someone has to go first. The irony? Those who lead gain the biggest advantage.
11. **"Not invented here"**
    In large companies, new tech needs to clear internal technical reviews. If a few gatekeepers—often unfamiliar with LIBS—aren't convinced, the proposal dies. Worse, if they've backed a competing technology, they'll see LIBS as a threat rather than an opportunity.
12. **"I saw it fail once"**
    Early LIBS systems overpromised and underdelivered, leaving some skeptical. Technology improves, but bad first impressions linger. Demonstrating reliability in the field is the only way forward.
13. **"Need a lab coat to use it"**
    Users don't want a screen full of spectral peaks—they want clear, actionable answers. Red light, green light. Weight percent, ppm. LIBS needs to shift from delivering data to delivering decisions.
14. **"Lab techniques are more trusted"**
    Decades of regulatory validation give traditional methods an advantage. LIBS is still proving itself, and most industries are risk averse. Change comes slowly, but real-world results will tip the scales.
15. **"It's too new"**
    The same concern as the previous point, but from managers instead of scientists. They'd rather wait until LIBS is an industry standard.
16. **"Too much data, not enough insight"**
    LIBS generates a flood of spectral data, but many users don't know what to do with it. Why would they? LIBS providers need to move from raw output to tailored, actionable insights.
17. **"Doesn't fit my workflow"**
    If adopting LIBS means changing how people work, resistance is inevitable. The better approach? Make LIBS enhance their workflow, not upend it.
18. **"Changes how we do things"**
    The management version of the previous point. Even if LIBS is better, change is disruptive—and inertia is powerful. Adoption takes time, but the trajectory is clear.

the level of individual crops. Samples are taken, sent to a lab, and returned weeks later. The result? Wasted inputs, uneven yields, and declining soil health.

We built a LIBS system that moves at the speed of modern farming. Mounted on a tractor, it scans soil in real time, generating high-resolution nutrient maps on the fly. Instead of broad assumptions based on a handful of samples, farmers now see precise nutrient variability across entire fields, down to each plant. In trials, our system kept consistency below 5% error across thousands of readings—double the accuracy of traditional lab methods. The impact is tangible: farmers spending $200 per acre on fertilizer cut waste by 30%, saving $60 per acre while boosting yields. Multiply that across millions of acres, and the economic and environmental gains are undeniable.

Mineral Exploration: Compressing Years into Months

Mining exploration is a game of patience and probability. A single site assessment takes years, and decisions hinge on geochemical data that arrives months after samples are collected. The cost of delay is measured not just in dollars but in missed opportunities.

LIBS shrinks that timeline. In field trials, our system scanned over 10,000 spots per day, achieving 95% correlation with lab techniques. Instead of waiting weeks for results, geologists had real-time elemental data in seconds. The difference was immediate: one evening scan revealed an anomaly two kilometers from a planned drill site. The next morning, the drill plan changed. The result? Faster discovery, lower costs, and decisions driven by real-time insights rather than historical averages.

The economics are real: tenfold acceleration in exploration, a 90% reduction in analytical expenses, and a direct path to faster resource discovery. In an industry where a single delay can cost millions, real-time data isn't just an advantage—it's a necessity.

LIBS While Drilling: The End of Core Extraction

For decades, the standard method for analyzing geological formations has been drilling, extracting core samples, and sending them to a lab. Each step adds cost, time, and uncertainty. The process is so ingrained that few questioned whether it was necessary—until now.

Our LIBS-while-drilling system integrates directly into standard drill bits, providing real-time geochemical data at sub-centimeter resolution. There is no waiting for core transport and logging because there are no cores, just instant, reliable data.

Trials demonstrated 97% repeatability, with detection limits below 1% by weight for most elements—previously unthinkable in downhole environments.

The impact? A $500,000 reduction in per-hole drilling costs and a shift from reactive to proactive exploration. What once took months now takes minutes, enabling geologists to assess formations while drilling rather than after the fact. We developed this LIBS tech for lunar missions, but its greatest impact may be right here on Earth.

From Speculation to Verification: The LIBS Advantage

Carbon markets depend on one thing: proof. But verifying carbon sequestration is slow, expensive, and riddled with uncertainty. Without reliable measurement, financial incentives collapse, and investment stalls.

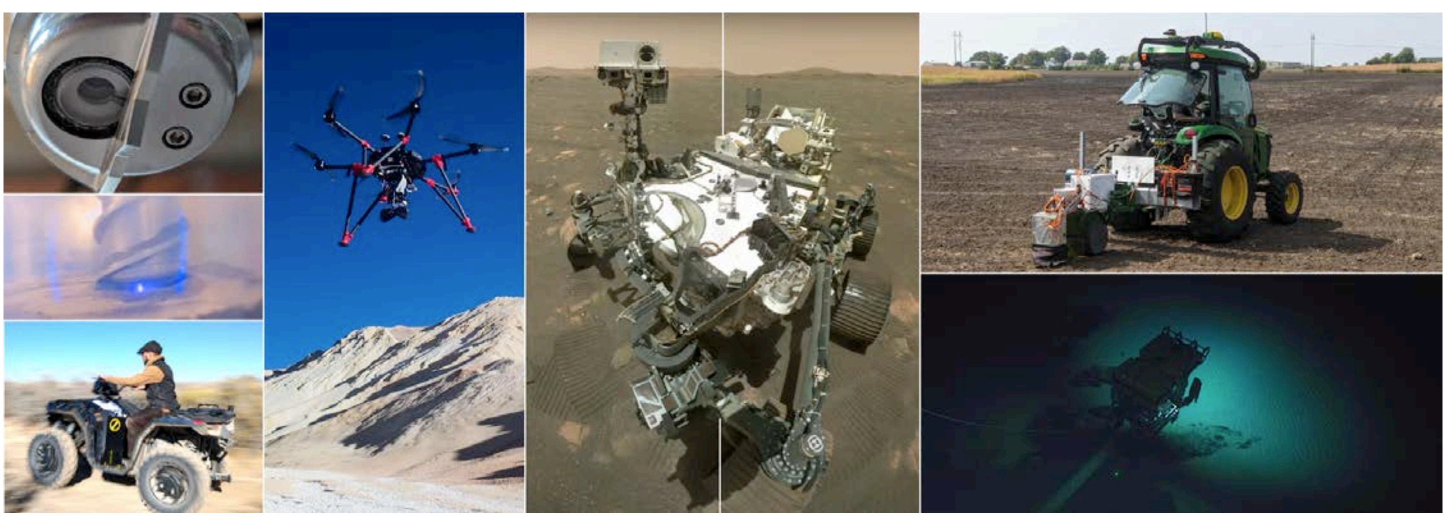
LIBS changes that by making mineralization measurable in real time. Cement production, water desalination, enhanced rock weathering (ERW) in soil, and ocean alkalinity enhancement (OAE) all promise massive carbon sinks—but without data, they remain theory. The real problem isn't just the delay; it's the lack of granularity and scale in verification, limiting both insight and value.

Our LIBS tracks mineralization with 90% accuracy and 6% stability, allowing companies to optimize and verify sequestration as it happens.

This isn't just about measurement—it's about turning data into a tradable, verifiable assets. LIBS replaces hazy models with hard metrics, converting carbon capture from model estimate into auditable commodity: the bedrock for robust markets where every tonne is verified.

Space Life Support: Closing the Loop

LIBS' journey from Mars to industry now returns to space in a fitting symmetry. Our systems are set to probe Venus' clouds for signs of chemistry at the edge of habitability and to map mineable



Mars Heritage, Earth Impact. Impossible's LIBS technology operates where others can't. Born from planetary exploration, it now drives real-time geochemical analysis in mining, agriculture, and subsea resource mapping—proving value across the most demanding environments.

resources on the Moon. But LIBS most surprising frontier isn't exploration—it's survival.

Life support (NASA's way of saying "keeping people alive in space") leaves no room for guesswork. Water and plant nutrients require constant monitoring, yet current methods rely on manual sampling and Earth-based labs—a logistical dead weight when, quite literally, every gram counts. Future off-world stations won't have that luxury.

We applied LIBS technology to create a fully autonomous nutrient monitoring system. It detects macronutrients and trace elements with 10 ppm precision in under a second, making real-time adjustments possible. The system extends to potable water monitoring and contaminant detection, ensuring closed-loop resource management in space.

NASA is already validating the hardware, with upcoming parabolic flights set to test performance in microgravity. The goal is clear: replace slow, manual processes with real-time, autonomous control. What started as an instrument for Mars exploration is now the key to sustaining human life beyond Earth.

The Impossible Way: Why It Works

Our success where others struggled comes down to four principles:

1. Start with the problem, not the technology. We don't build LIBS for its own sake. We solve industry challenges where LIBS is the best tool
2. Prove economic value first. Adoption follows clear financial benefits, not technical specifications
3. Integrate seamlessly. Systems fit into existing workflows instead of forcing disruptive change
4. Deliver complete solutions. Beyond instruments, we provide AI-driven analytics, automation, and decision-ready insights

These aren't just principles—they're the reason LIBS is no longer on the sidelines. The barriers that once held it back—cost, complexity, and skepticism—are giving way to proof, performance, and economic value (*11*). The question isn't whether LIBS will become standard—it's who will act in time to capture its full advantage.

THE LIBS TIPPING POINT

Early adopters aren't just working faster—they're cutting costs, reducing waste, and making better decisions. What once took weeks in a lab now happens instantly on-site, in factories, and in the field. LIBS speed and precision are driving efficiency where it matters most. This transformation didn't happen overnight, and it didn't happen in isolation. Decades of work across academia, industry, and government laid the foundation. Customers willing to challenge convention made it real. To the researchers, engineers, business leaders, and early adopters who pushed LIBS forward—this moment belongs to you.

The technology is mature. The applications are proven. The returns speak for themselves. LIBS is no longer an emerging tool—it is a necessary one. The only thing left is for industries to decide whether to use it or watch others pull ahead.

ABOUT THE AUTHOR

After retiring from international basketball in 2005, Pablo got his PhD in physics in 2008 and worked through an alphabet of space organizations, NASA, CSA, and SETI among others.

His work in planetary science has won many awards, including NASA GAAs, the highest level of peer-nominated awards given to NASA teams.

In 2016 Pablo set up Impossible Sensing to crack impossible problems in space and industry. His approach: look where others don't. The breakthroughs followed.

Success bred success: technology firsts in energy, ocean, and agriculture led to three more startups—all speeding the green transition. Bold innovations followed. More industry awards, too.

Today Pablo leads a team turning space-proven sensing into climate tech, delivering in weeks what takes others years.

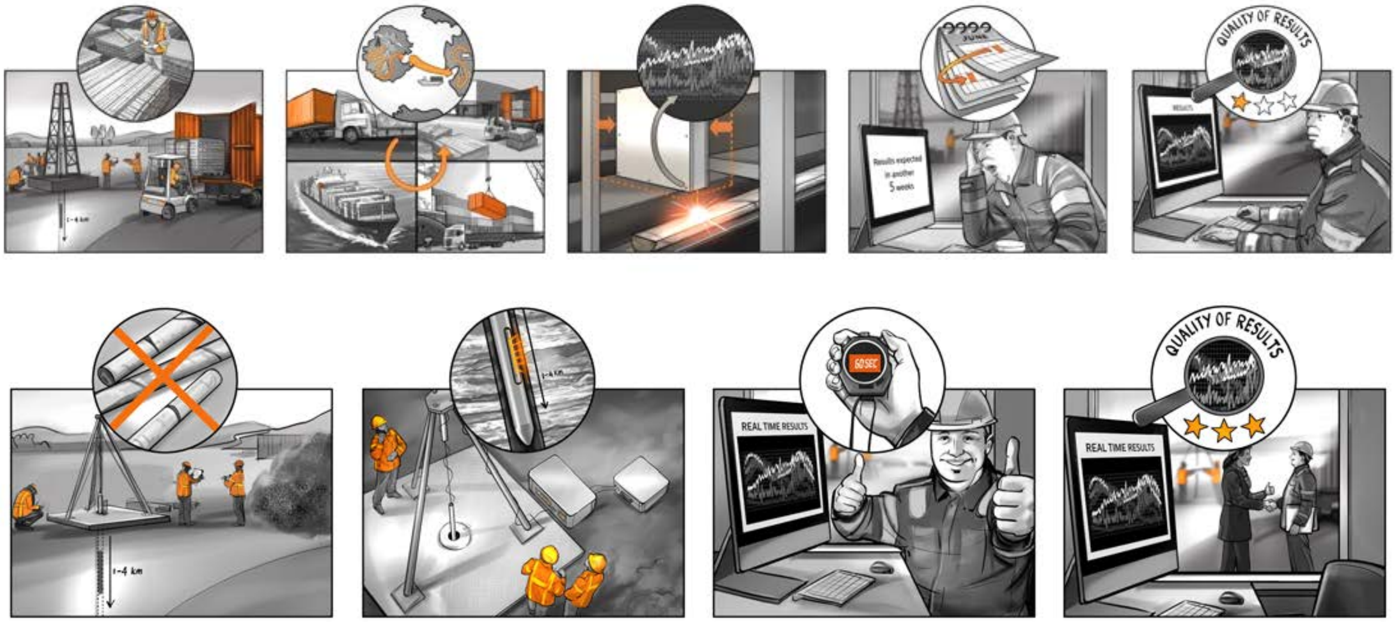
Box 4: Lessons From Failure—The Startup Journey

My path to solving LIBS adoption began with a spectacular failure. In 2013, I founded MalaUva Labs—Spanish for "sour grape," a nod to both my roots and my frustration with slow technology adoption. Our goal was simple: take the LIBS technology we had proven on Mars and make it indispensable on Earth. Our first big bet was borehole analysis. Partnering with Honeybee Robotics and Applied Photonics, we developed a system to deliver real-time geochemical profiles straight from blast holes. The technology worked. NASA backed it. A major mining equipment manufacturer invested. On paper, everything was in place.

Then the market collapsed. When commodity prices crashed in 2014, mining companies slashed innovation budgets overnight. Despite technical success, I hadn't answered the only question that mattered during a downturn: how does this save money today? I could quantify elements down to 5 ppm, but I hadn't quantified the savings in dollars per ton. That failure reshaped everything. I learned the hard way that technology alone changes nothing—business value does. Companies don't buy specs; they buy impact.

That realization became the foundation for Impossible Sensing. We flipped the model: start with customer problems, prove the financial case, then build the technology to fit. This shift also freed us from the gravitational pull of any single industry. Unlike many startups that refine *one* product, we move fast, solve hard problems, and move on. To do this, we rely on hit-and-run experiments—wild ideas that shouldn't work, and usually don't. But sometimes, we find a pearl. This approach isn't for the faint of heart; it's mentally, physically, and financially punishing. But it works. And it keeps us ahead.

LIBS has followed the classic hype cycle—early excitement, inevitable skepticism, and now a steady climb as real value emerges. We've seen this pattern before with industrial automation, AI, and even X-ray fluorescence before it became standard. LIBS is crossing the same threshold. But the future isn't just LIBS alone—it's LIBS fused with other techniques. AI is sharpening spectral analysis. Multimodal sensing—combining LIBS with Raman and hyperspectral imaging—is expanding its reach. What started as an untested space technology is becoming an industrial workhorse. Every industrial revolution follows the same script: a few act early, define the standard, and lead. The rest adapt or fade. LIBS is at that moment now.



From Lab Lag to Real-Time Intelligence

(Top) Ship it, wait weeks, guess in the meantime—an industrial ritual that drains time, money, and efficiency. (Bottom) LIBS ends the wait. Instant, high-quality data where decisions are made. From mines to farms to factories—decisions made at the speed of business, not laboratories.

NOTES AND REFERENCES

1. In 2017 we partnered with a major mining firm to develop the first fully autonomous drone-based sample survey and acquisition system. Honeybee Robotics engineered a scoop capable of handling everything from fine sediments to solid rock. The system was fully automated: navigation, region-of-interest targeting, landing, analysis, and sample return. We field-tested it at 5,200 meters along the Chile-Bolivia border—a copper prospect. The drone, modified for thin-air flight, completed a 5 km round trip without exhausting its battery, ascended 80 meters, and retrieved multiple samples—including >500g rocks using an innovative claw gripper. The test proved what had never been done before: remote, autonomous sampling in extreme terrain. With demand for critical minerals surging, interest in this capability has only grown. The ability to reach deposits in hazardous or inaccessible locations—without risking human safety—offers a strategic edge in mineral exploration. Here's a video of it in action: https://www.youtube.com/watch?v=rRqOZmvj8RY
2. https://www.irena.org/Digital-Report/Geopolitics-of-the-Energy-Transition-Critical-Materials#page-0
3. P.G. Pardey and J.M. Alston. (2023) The Drivers of U.S. Agricultural Productivity Growth. Federal Reserve Bank of Kansas City, https://www.kansascityfed.org/documents/7107/the-drivers-of-us-agricultural-productivity-growth.pdf
4. LIBS foundations are well covered in the literature. For a deeper dive, Reinhard Noll's *Laser-Induced Breakdown Spectroscopy: Fundamentals and Applications* is a solid reference.
5. Laser technology has evolved from maintenance-intensive behemoths to compact, reliable solid-state devices. Spectrometers have shrunk from room-sized instruments to miniaturized components with superior resolution. Computing power now enables complex spectral processing in milliseconds on portable devices. These convergent advances have created LIBS systems that deliver laboratory-quality analysis in field conditions, operated by personnel with minimal-to-zero training. Getting these elements to work together in a lab is a feat. Getting them to work 140 million kilometers away, in Mars' brutal conditions, seemed impossible. Yet that's exactly what happened.
6. It all started in 2004. Two small rovers, Spirit and Opportunity, had just landed on opposite sides of Mars. Viking and Pathfinder came before them—pioneering missions, but with limited tools. They gave us data, but mostly more questions. Spirit and Opportunity aimed higher, carrying the best instruments NASA had ever sent to Mars. Steve Squyres' *Roving Mars* captures the full story: the uphill battle for funding, the engineering marathon, the nerve-wracking landings, and the years of unexpected survival. Against all odds, the rovers kept rolling. Yet, for all their success, the twin rovers were essentially advanced cameras on wheels—thermal imagers, X-ray spectrometers, and iron detectors. They hinted at Mars' history but couldn't give definitive answers. Twenty years later, we're still debating whether Opportunity actually found jarosite—a key mineral that could confirm Mars was once wet and warm. (I based half my PhD on that discovery, studying the geochemistry of acid mine drainage sites before shifting to building the machines that would look for life beyond Earth.) The problem wasn't the scientists—some of the world's best geologists work remotely on Mars. The limitation was the technology.

   Enter Curiosity. The size of a small car, it was NASA's bold bet that Mars had once been habitable. This time, they packed it with every tool possible—X-ray diffraction, fluorescence, ground-penetrating radar, mass spectrometry, gas chromatography, infrared cameras. And LIBS.

   LIBS had spent decades in development at LANL, but spaceflight was another level. Roger Wiens, already a veteran of missions like Genesis, fought to get it on board. It wasn't an easy sell. LIBS, an untested technique for planetary science, had to level up to century-old gold standards like X-ray diffraction and GC-MS. It made the cut. *Red Rover*, Wiens' book, tells that story.

7. Operating a Mars rover isn't cheap. The Planetary Society reported that running Curiosity costs roughly $200,000 per day—covering mission control, data analysis, and rover operations. Every movement, measurement, and experiment is planned with precision to maximize scientific return. Time lost is money burned. Driving to a target takes days. Preparing and analyzing a sample takes even longer. LIBS changed that equation. Instead of grinding, scooping, and processing, Curiosity's ChemCam fires a laser, analyzes the plasma, and delivers elemental data in seconds—at zero cost in mobility, power, or mission time. It's the difference between spending a week investigating the wrong rock and making an instant, informed decision to move on.
8. As I write this, 25 sealed sample tubes await pickup on Mars. When they'll come back isn't clear, but SuperCam has already done its job—delivering rapid, high-value science while avoiding costly mistakes. And by mistakes, I don't mean errors—what's a dud for one scientist might be gold for another. Deciding which samples are worth returning is a constant, rigorous debate among over 1,000 geologists, chemists, and planetary experts. But this is still rocket science, and every sample slot is precious.

   According to Spaceflight Now, each returned sample will cost *at least* $250 million. If SuperCam prevents just one low-priority sample from being collected, it recoups its entire cost many times over. That's an astonishing return on investment, and with half a million laser shots fired since 2021, we're already well past that mark.
9. SuperCam exists because NASA made a choice: Curiosity's onboard lab was too complex, slow, and expensive. For Perseverance, they removed it entirely, shifting to fast, stand-off analysis in real time. The results speak for themselves—unprecedented geological mapping and the first steps toward selecting Mars samples for return to Earth. NASA led the way, and others followed. Today, LIBS is fully embedded in planetary exploration. China has deployed a version on Mars. India has already used it on the Moon. Commercial space missions are integrating it to search for mineable lunar resources—rocket fuel, construction materials, and even helium-3.
10. The explosion of handheld LIBS devices should have been a breakthrough. Instead, it became a cautionary tale. A market saturated with nearly identical, power drill-shaped analyzers—descended from older XRF tools—has driven a race to the bottom in both price and performance. When every product looks the same, innovation stalls. A mining executive put it bluntly: "We bought three, and each gave different results on the same sample." Another AI-driven mining company admitted their handheld LIBS sits unused in storage—there's no way to integrate the data into their workflow. The gap between capability and adoption isn't about technology anymore. It's about institutional inertia, integration, and trust—the real hurdles LIBS must overcome. Users need answers, not spectra. LIBS has been in the market for over 20 years and has proven itself on Mars—it's hardly bleeding-edge technology at this point.

    The most successful implementations start small, deliver quick wins, and expand gradually as users see tangible benefits.
11. Looking back at these field experiences, I've seen how addressing the barriers I outlined earlier transforms skeptics into advocates. Time and again, the same pattern emerges: Technical implementation must be seamless. LIBS needs to integrate directly into existing workflows—mounted on vehicles, feeding data to familiar software, operating reliably in harsh conditions without PhD-level expertise. Economic value must be immediate and obvious. We've proven all this in many settings. Mining companies see a 10x acceleration in discovery rates, cutting exploration costs by 90% per site. Agricultural pilots show potential for 10% yield improvements through precision soil management. In both cases, the ROI isn't theoretical—it's measurable in days, not years. Cultural adoption requires trust-building. We've learned to position LIBS as complementary to existing methods, starting with applications where traditional techniques struggle most. As users see LIBS outperforming lab results in specific applications, resistance naturally fades.