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Lunar Radius Framework:
Grounded Operational Radius Design for Lunar Designated Areas

Aaron Mackey

July 2026

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The framework gives lunar mission operators a proportionate, physics-founded method for sizing the areas around their operations, and gives reviewers a shared technical baseline for evaluating them. Whether an operator is sizing an area for the first time, negotiating one as a mission evolves, or contesting another operator's, the goal is the same: replace assertion with evidence, and make the reasoning chain public.

Key points

No operational standard exists for sizing lunar areas. When operators design operational radii for Designated Lunar Areas (DLAs), they have nothing to bank on, so radii get invented ad hoc — producing oversized claims, ambiguity under Article II of the Outer Space Treaty, and conflict risk where areas overlap.

Physics is a shared language where governance frameworks are not. The framework replaces political assertion with documented If/Then reasoning chains grounded in measurable physical phenomena. Dust disperses according to the same models regardless of which treaty an operator has signed.

Areas should be designed to shrink, not expand. An area claimed under low confidence should contract once mission data validates a smaller radius. Without time-bound review, a long-held area functions as de facto appropriation — the very problem the framework exists to prevent.

Aaron Mackey was a 2026 Research Fellow at the Open Lunar Foundation. His fellowship project built the Lunar Radius Framework, a browser-based tool for sizing operational areas around lunar activity, together with two documented scenario simulations and an integration path into the Lunar Ledger.

Disclaimer

The views and opinions expressed in this paper are those of the author as part of a Research Fellowship at Open Lunar Foundation, and do not reflect the opinions or views of any organisation the author is affiliated with, including current and prior employers.

This document is not a regulatory instrument. It is a practical reference for mission planning and operations, written for lunar mission operators, mission planners, and the governance bodies that currently do, or may in future, regulate operational claims.

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Contents

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Terms used

Term	Definition
Designated Lunar Area (DLA)	An area declared around lunar hardware or activity, within which other operators face notification or entry obligations.
Core operations area	The innermost ring. No entry by any other operator; a hard prohibition with no due-regard exception.
Buffer (Harmonization) area	The middle ring. Restricted operations by others, with active coordination required. Notify the core operator and receive acknowledgement before entry. Spelled as in the OLF Field Guide.
Coordination area	The outer ring. Operations by others permitted with prior notification; due regard applies, but unilateral operations are allowed after notice.
If/Then chain	The documented reasoning that connects a measured hazard to a computed radius, published so that any reader can verify the claim.
Confidence multiplier	A factor applied to a declared hazard rate to reflect stated uncertainty. Lower confidence produces a larger area.
Mitigation factor	A reduction applied to the effective hazard load where physical mitigation, such as a berm or full enclosure, is in place.
Selenographic coordinates	Lunar latitude and longitude, referenced here to IAU:30100 rather than the terrestrial WGS84.
Permanently shadowed region (PSR)	Lunar terrain that never receives direct sunlight, and therefore may retain water ice.

Some figures in this paper label the rings as "zones", following the earlier terminology of the OLF Field Guide. The text uses "area" throughout.

Executive Summary

Activity is converging on the Moon's south pole. When lunar operators design operational radii for Designated Lunar Areas (DLAs), they have no operational standard to work from. Without one, operators invent radii ad hoc, which leads to oversized territorial claims, ambiguity about appropriation under Article II of the Outer Space Treaty, and conflict risk where areas overlap.

The framework replaces political assertion with documented If/Then reasoning chains grounded in measurable physical phenomena. It answers two questions: what is the minimum operational radius for a given lunar activity that will actually keep people safe and equipment protected, and how should that radius scale as operations mature?

What this deliverable includes

- Live tool: aaronmac24.github.io/lunar-radius-framework
- Source repository: https://github.com/openlunar-dev/designated-lunar-areas-groundrules
- Two fully documented scenario simulations: Scenario A, an ice-mining dispute at Shackleton Crater; Scenario B, a multi-operator power station renegotiation
- A standards and protocols section covering data schemas, GeoJSON output specifications, and Lunar Ledger integration
- Requirements for a future computational simulation build-out
- Synthesised insights from stakeholder interviews with Volta Space, Blue Origin, and Magna Petra
- Known limitations and open questions for the next development phase

1. Product Description

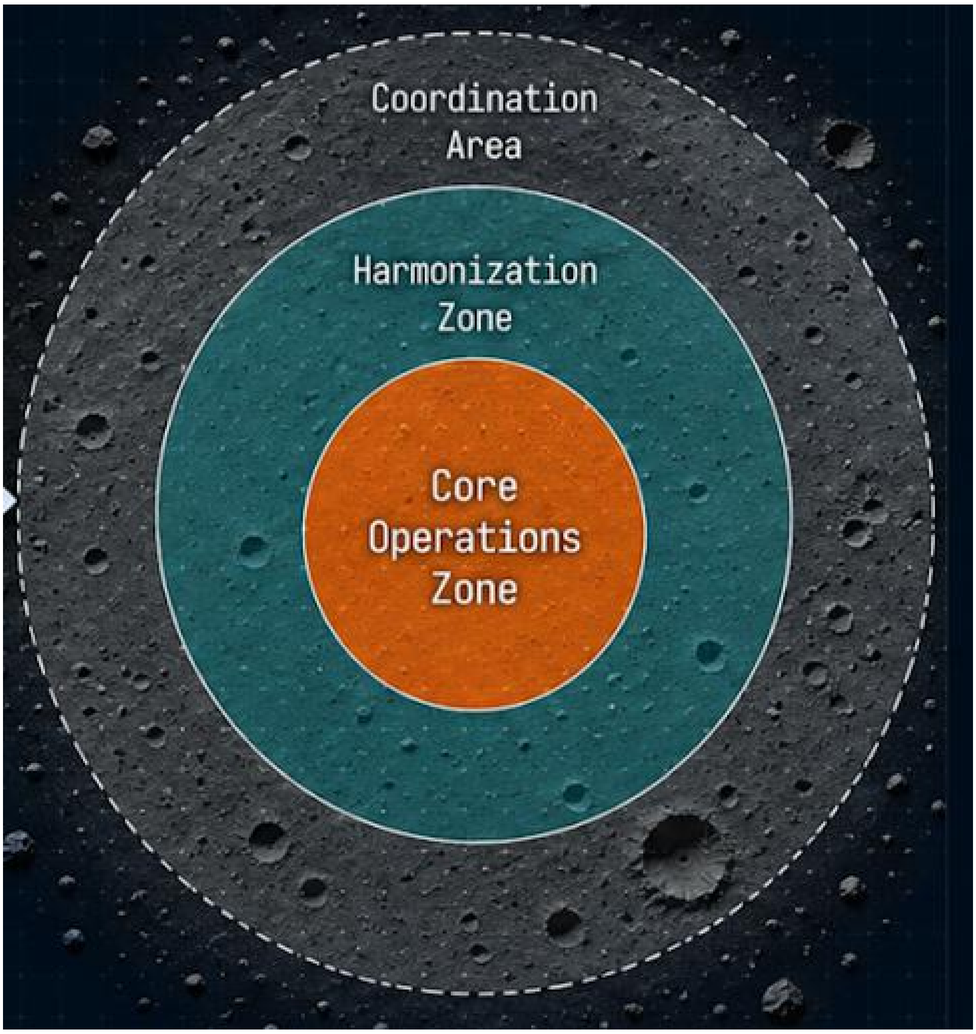
The Lunar Radius Framework is a browser-based application that accepts a hazard type and production rate, applies confidence and mitigation modifiers, and outputs three concentric operational areas as GeoJSON in selenographic coordinates (International Astronomical Union reference IAU:30100). Developed at the Open Lunar Foundation, it implements Christine Tiballi's three-ring DLA framework (OLF Field Guide, September 2025) in executable form.

1.1 The core logic

The framework answers a single question in a fixed form: if a given hazard type produces X units, then the minimum proportionate operational radius is Y km. This is not a regulatory prescription. It is a computation grounded in measurable physical phenomena.

An operator claiming a core operations radius larger than the framework output must justify the excess in technical terms rather than political ones. The Buffer and Coordination areas, by contrast, are defined over time through operator coordination.

Area	Default multiplier	Governance meaning	Obligation
Core operations	1× core radius	No entry by any other operator	Hard prohibition; no due-regard exception
Buffer (Harmonization)	2.5× core radius	Restricted operations by others, with active coordination	Notify core operator and receive acknowledgement before entry
Coordination area	5× core radius	Operations by others permitted with prior notification	Due regard; unilateral operations after notice



The three-ring structure the framework computes. Image credit: Aaron Mackey, Open Lunar Foundation, after the three-ring DLA framework (OLF Field Guide, 2025)

1.2 Two input modes

Dust mode (primary hazard)

For operations where lunar dust is the governing hazard, such as lander plumes, rover traversals, and mining. The mode uses a power-law formula calibrated to lunar dust transport literature:

```
core_radius = 0.5 × effective_dust^0.50  [km]

effective_dust = dust_rate × (1 + confidence_fraction) × mitigation_factor
```

The leading coefficient of 0.5 and the square-root scaling are provisional, chosen to produce kilometre-scale outputs consistent with ICES-2023-120 plume deposition data. They must be replaced with values derived from mission-verified lunar dust transport models once that data is available from operators such as ispace or the Japan Aerospace Exploration Agency (JAXA). This is the highest-priority open calibration item.

Manual hazard mode

For any other hazard type: thermal output (MW), radio-frequency (RF) emissions and electromagnetic interference (EMI, in mW), ionising radiation (mSv/hr), debris ejecta, or a custom hazard. The operator defines a linear ratio, in the form of X units of hazard mapping to Y km of core radius.

The ratio is the If/Then logic itself. It is intentionally linear, because the governance purpose is transparency: anyone reading the ratio can verify the claim. Area multipliers are separately adjustable, so that different governance architectures can be applied to different hazard types.

1.3 Outputs

Output format	Purpose	Compatible tools
GeoJSON (IAU:30100)	Geospatial area polygons for analysis in a geographic information system (GIS) and for Lunar Ledger submission	QGIS, Felt, geojson.io, Lunar Ledger
buffers.json	Pre-converted pixel values for the OLF lunar simulator (App.jsx)	Vic Paulson's Lunar Overlap simulation
URL deep-link	Lunar Ledger integration; mission coordinates pre-populate the tool	Lunar Ledger mission detail view

1.4 Confidence and mitigation standards

Confidence level	Multiplier	Use when
High (±10%)	1.10×	Empirical data from a prior mission or a validated test
Medium (±25%)	1.25×	Engineering model, with no lunar validation yet
Low (±50%)	1.50×	Analogous Earth data, with significant uncertainty
Unknown	2.00×	No supporting data; worst-case assumption required

Mitigation level	Reduction factor	Definition
None	1.0× (no reduction)	No physical mitigation of the hazard source
Partial berm or shield	0.6× effective load	Passive barrier reducing line-of-sight exposure
Full enclosure or suppression	0.35× effective load	Active suppression or complete containment

1.5 Live tool and source files

- Live tool: aaronmac24.github.io/lunar-radius-framework
- Source repository: https://github.com/openlunar-dev/designated-lunar-areas-groundrules
- Source files: index.html, style.css, framework.js. No build step required; open index.html directly, or serve with python -m http.server 8000
- Simulator integration: SIMULATOR_PATCH.md in the repository root

2. Scenario A

Shackleton Crater, south pole, 2029. An ice-mining dispute between Artemis and ILRS operators.

2.1 Scenario description

It is 2029. Company A, an Artemis Accords signatory, and Company B, an International Lunar Research Station (ILRS) aligned consortium, both plan water-ice extraction at Shackleton Crater. Company A arrives first and claims a 50 km "safety zone" around its operations. Company B arrives later, views this as de facto appropriation of the crater rim, and files a complaint with the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). Both operators need buffer areas, but neither has an evidence-based methodology for sizing them.

This is the central governance failure the framework is designed to address. In the absence of a shared standard, the first mover sets the precedent through political assertion rather than technical evidence.

2.2 Environmental inputs

Parameter	Value	Source	Confidence
Dust production rate	500 kg/hr	Engineering estimate, ice extraction operations	±50% (Low; no lunar validation)
Ambient accumulation	23.4 µg/cm^2 per 12-day cycle	Li et al., Chang'E-3, Mare Imbrium	High; measured
Lander plume deposition	~1 mg/cm^2 per event within 5 km	ICES-2023-120 (Texas Tech, 2023)	Medium; laboratory model
Single event vs ambient	~43× one 12-day ambient cycle	Derived from the above	Medium
Site latitude/longitude	89.9°S / 0.0°E	Shackleton Crater rim, south pole	High

Parameter	Value	Source	Confidence
Mitigation	None assumed (worst case)	Baseline scenario	Not applicable

2.3 If/Then logic chain

Step 1: Establish the governing hazard

If the primary operation is ice extraction using mechanical excavation and lander resupply, then the governing hazard is lunar dust, measured as a production rate in kg/hr, with a secondary hazard from lander plume events.

Step 2: Select the confidence level

If the dust production estimate of 500 kg/hr is based on terrestrial engineering models without lunar mission validation, then the confidence level is Low (±50%), applying a 1.50× worst-case multiplier.

```
worst_case = 500 × 1.50 = 750 kg/hr
```

Step 3: Apply mitigation

If no physical mitigation — berm, shield, or enclosure — is in place at the start of operations, then the mitigation factor is 1.0, meaning no reduction.

```
effective = 750 × 1.0 = 750 kg/hr
```

Step 4: Compute the core radius

Applying the dust mode formula:

```
core = 0.5 × 750^0.50 = 0.5 × 27.4 ≈ 13.7 km
```

Step 5: Compute all three areas

Area	Formula	Radius	Governance action required
Core exclusion	1× 13.7 km	13.7 km	No entry. Company B's operations must clear this boundary.
Buffer / Harmonization	2.5× 13.7 km	34.3 km	Company B must notify Company A before any operations within this ring.
Coordination area	5× 13.7 km	68.5 km	Company B must give prior notice. No veto right, but due regard is required.

Step 6: Compare to Company A's claim

Company A claim	Value	Framework output	Status
Safety zone radius	50 km	13.7 km core / 34.3 km buffer	The claim exceeds the 34.3 km harmonization buffer and sits inside the coordination area, where prior notice is required but unilateral operations are permitted. It is not proportionate as an exclusion boundary.
Justification provided	None; political assertion	Documented If/Then chain above	Company A must provide a peer-reviewed dust model supporting 50 km, or scale to the framework output
Governance implication	De facto appropriation claim	Evidence-based coordination area	The framework reframes the dispute from territorial to technical

2.4 Resolution pathway

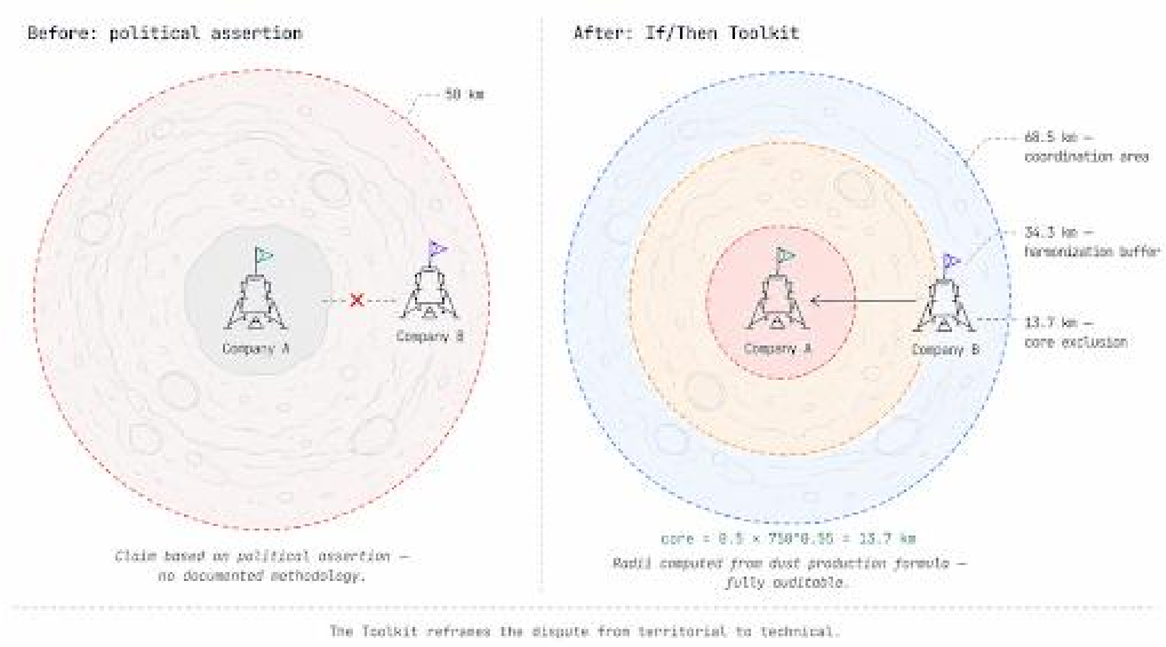
COPUOS reviews both operators' claims against the framework's documented If/Then chain. Company A is asked a specific question: its mission type is water-ice extraction, and the framework, using its own stated dust production of 500 kg/hr at Low confidence, computes a 13.7 km core and a 34.3 km harmonization buffer. Its 50 km claim exceeds the harmonization buffer and falls inside the coordination area, where notice is required, but no veto right exists. What data supports treating that as a hard exclusion boundary?

Company A has two credible options:

1. Provide peer-reviewed data showing that dust transport exceeds 50 km under mission conditions. This becomes new precedent, expanding the framework's validated envelope.
2. Scale to the framework output of a 13.7 km core, and document the reasoning behind the initial 50 km claim.

Company B gains an evidence-based counter to the appropriation claim: a physics argument rather than a geopolitical one. Both operators submit their If/Then documentation to the Lunar Ledger, creating a public record of the radius-reasoning chain for future audit.

This is how the framework bridges the Artemis and ILRS divide. Neither side needs to accept the other's governance regime. Both sides can accept the physics. Dust disperses according to the same models regardless of which treaty an operator has signed.



Scenario A before and after. On the left, a single 50 km boundary asserted without supporting method, and a dispute with no shared basis for resolution. On the right, three computed radii, each traceable to a declared dust production rate and confidence level. The claim itself may survive review; what changes is that it now has to be argued in technical terms. The formula annotation in this figure predates a correction to the exponent; the computation shown is $0.5 \times \sqrt{750}$, as given in Section 1.2. Image credit: Aaron Mackey, Open Lunar Foundation

2.5 GeoJSON output for this scenario

The following URL opens the framework pre-populated with Scenario A parameters at the Shackleton Crater rim: Scenario A deep-link

Downloading the GeoJSON from this configuration produces a FeatureCollection with three polygon features — coordination, buffer, and core — and a site point, all in IAU:30100. This file can be submitted directly to the Lunar Ledger as the operator's area declaration.

2.6 Lunar Ledger submission template

The following fields should accompany any GeoJSON submission to the Lunar Ledger for a dust hazard scenario.

Field	Value (Scenario A)	Notes
Operational radius (km)	13.7	Core exclusion radius; the minimum safe exclusion
Hazard type	Dust	Primary governing hazard
Dust production (kg/hr)	500	Operator-declared; peer review recommended

Field	Value (Scenario A)	Notes
Confidence level	Low (±50%)	Must be declared; drives the worst-case multiplier
Mitigation	None	Update if a berm or shield is installed mid-mission
Area declaration date	[date]	For temporal review tracking
Area review period	18 months	Recommended; recompute as confidence improves
Linked GeoJSON	[URL]	Attach the exported .geojson file
If/Then rationale	[link to this document]	The full reasoning chain must be publicly accessible

3. Scenario B

A multi-operator site, 2031. Thermal and EMI radius renegotiation around a power station.

3.1 Scenario description

It is 2031. Five operators are active near the lunar south pole. Operator D runs a nuclear fission power station. Operator C operates an adjacent habitat. Operator E runs a communications relay hub.

Operator D's thermal output rises from 500 to 750 MW because of equipment degradation, requiring a radius expansion. At the same time, D's degraded power management produces electromagnetic interference that disrupts E's communications windows. Operator C's habitat DLA sits immediately adjacent to D's original 8 km boundary, so any expansion creates an overlap and forces a renegotiation.

3.2 Framework application: dual hazard computation

Thermal hazard layer

Parameter	Baseline (operational)	Degraded state	Notes
Thermal output	500 MW	750 MW	Equipment degradation mid-mission
Confidence	High (±10%)	Medium (±25%)	Uncertainty increases because the degradation is novel
Mitigation	None	None	Shielding under consideration

Parameter	Baseline (operational)	Degraded state	Notes
Core radius	~8.0 km	15.0 km	Computed via manual mode. The 0.016 km/MW ratio is derived from the unmultiplied 500 MW ➜ 8 km baseline; the confidence multiplier is then applied to the declared output, not to the ratio.

```
baseline ratio: 500 MW → 8 km, so ratio = 8/500 = 0.016 km/MW

degraded core = 750 × 1.25 × 1.0 × 0.016 = 15.0 km
```

EMI hazard layer

A second computation is run in manual hazard mode for the radio-frequency emissions.

Parameter	Value	Notes
Hazard type	RF emissions (mW)	Electromagnetic interference from degraded power management
Emissions level	To be measured by the operator	Requires in-situ measurement; use Unknown confidence until measured
Confidence	Unknown (2.00×)	No lunar EMI standard exists yet, so worst case is required
Coordination area	Separate computation required	Set the ratio from Operator E's interference threshold once measured

3.3 Three resolution options

Option	Technical approach	Radius outcome	Trade-off
1. Expand the area	No mitigation. Accept the new core radius.	15.0 km thermal core, plus an EMI coordination area	Conflicts with Operator C's habitat DLA. Requires C's agreement.
2. RF shielding	Install shielding on the power plant. Reduces EMI; thermal unchanged.	15.0 km thermal core. EMI area significantly reduced.	Capital cost of installation, and construction dust impacts.
3. Operational protocol	Reduce peak power during Operator E's critical communications windows.	12.0 km thermal core, from a peak held at 600 MW (600 × 1.25 × 0.016). EMI coordination area shrinks.	Operational complexity. Requires coordinated scheduling with E.

The outcome recorded in the original proposal is that Operator D implements RF shielding and agrees to a power scheduling protocol, with peak output held at 500 MW during E's critical windows. That stabilises the thermal core at 10.0 km (500 × 1.25 × 0.016), with the EMI coordination area nested within it. The figure exceeds D's original declared boundary even at the original power level, because confidence has fallen from High to Medium — uncertainty introduced by the degradation costs D radius it cannot recover by scheduling alone. Operator C's habitat remains viable. The negotiation uses the framework's documented ratios as the shared reference rather than political leverage.

3.4 Key insight from Scenario B

Scenario B demonstrates the framework's value beyond initial area-setting: it provides a shared reference for mid-mission renegotiation. Without a documented If/Then chain from the original declaration, D has no documented basis for the expansion, and C has no basis for objecting beyond territorial instinct. With the framework, both operators work from the same physics, the same confidence levels, and the same multiplier structure. The dispute becomes a technical refinement rather than a territorial confrontation.

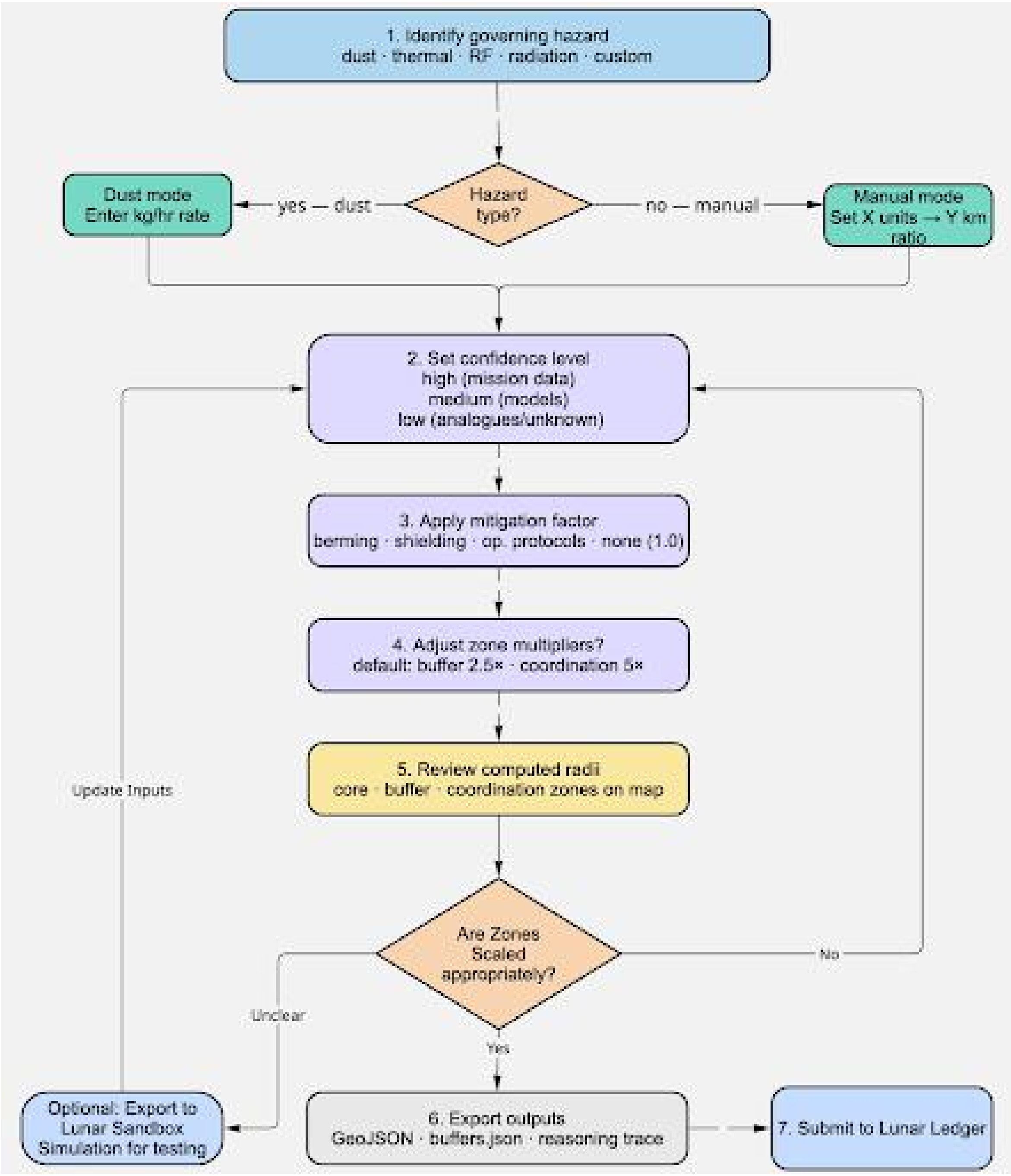
4. Running Alternative Scenarios

The framework is hazard-agnostic. Any physical phenomenon that creates a spatial exclusion need can be modelled in manual hazard mode. The following procedure applies to any scenario.

4.1 How to size, test, and declare an area

1. Open the tool at aaronmac24.github.io/lunar-radius-framework
2. Select "Manual hazard" mode from the toggle at the top of the input panel.
3. Select the hazard type from the dropdown, or select "Custom" and enter a name and unit.
4. Enter the hazard production rate in the appropriate unit.
5. Define the ratio in the Radius Ratio builder: X units mapping to Y km of core radius. Use the most conservative credible reference as the baseline.
6. Set the confidence level. Use High for mission-validated data, Medium for engineering models, Low for Earth analogues, and Unknown where there is no supporting data.
7. Set the mitigation factor. Leave it as None if no physical mitigation is in place.
8. Adjust the area multipliers if the governance context differs from the default OLF three-ring structure.
9. Enter the selenographic coordinates of the site.

10. Download the GeoJSON and the If/Then reasoning chain, which is documented in the trace panel.
11. Submit the GeoJSON and the documented rationale to the Lunar Ledger.



The full decision path from hazard identification to Lunar Ledger submission. The loop back from the scaling check is the part that matters for governance. An area that looks disproportionate sends the operator back to measure, mitigate, or justify, rather than forward to declaration. Image credit: Aaron Mackey, Open Lunar Foundation

4.2 Worked example: RF interference

Operator E's communications relay operates at 2.4 GHz. Operator D's degraded power management emits uncharacterised RF noise. E has measured an interference threshold: operations degrade if ambient RF power at E's location exceeds 50 mW.

- Hazard type: RF emissions (mW)
- Measured output: unknown; 500 mW used as a precautionary estimate
- Confidence: Unknown (2.00× multiplier), because no lunar RF standard exists
- Ratio: a 50 mW interference threshold mapping to a 3 km coordination boundary, estimated from E's operational specifications
- Mitigation: none initially

```
worst_case = 500 × 2.0 = 1000 mW

coordination = (1000/50) × 3 = 60 km  ← too large; reveals the Unknown confidence problem
```

This 60 km output is intentionally alarming. It correctly reflects what happens when an Unknown confidence level is applied to an uncharacterised hazard. The framework's role here is diagnostic: it forces D either to measure the actual emissions, improving confidence, or to install shielding, applying a mitigation factor. The large output is not a flaw. It is the governance signal that more data is required before the area can be considered proportionate.

4.3 Scenario templates

The following table summarises the input configuration for each scenario type documented in the proposal. Use these as starting points.

Scenario type	Mode	Hazard and unit	Suggested ratio	Confidence start
Ice extraction (A)	Dust	Dust production, kg/hr	Power-law formula (built in)	Low; no lunar validation
Power station thermal (B)	Manual	Thermal output, MW	Operator baseline: X MW → Y km	High, if from prior operations
EMI / RF interference (B)	Manual	RF emissions, mW	Derived from receiver threshold	Unknown until measured
Satellite disposal corridor	Manual	Custom: impact debris, kg	Engineering trajectory model	Low; novel use case
Radiation source	Manual	Ionising radiation, mSv/hr	ICRP limit as threshold	Medium; analogous data

Scenario type	Mode	Hazard and unit	Suggested ratio	Confidence start
Habitat thermal	Manual	Thermal output, kW	Smaller ratio than a power station	High; well characterised

ICRP refers to the International Commission on Radiological Protection.

5. Standards and Protocols

This section defines the data schemas, GeoJSON specifications, and Lunar Ledger integration requirements that operationalise the If/Then framework for future simulation and transparency tool development.

5.1 GeoJSON output specification

Property	Value or type	Required	Notes
type	"FeatureCollection"	Yes	Standard GeoJSON
properties.framework	String	Yes	"OLF DLA If/Then Framework v[version]"
properties.crs	"IAU:30100"	Yes	Selenographic latitude and longitude, not WGS84
properties.generated	ISO 8601 datetime	Yes	Audit timestamp
properties.inputs.mode	"dust" | "manual"	Yes	Input mode used
properties.inputs.confidence	String label	Yes	Must be human-readable, not just a multiplier
properties.inputs.mitigation	String label	Yes	"none" | "partial" | "full"
features[0]	Coordination area polygon	Yes	Outermost; rendered first
features[1]	Buffer area polygon	Yes	Middle ring
features[2]	Core exclusion polygon	Yes	Innermost; rendered last
features[3]	Site point	Yes	Hazard source location
features[*].properties.radius_km	Float	Yes	Actual radius in km for each area
features[*].properties.fill	Hex colour	Recommended	For unstyled GIS rendering

5.2 If/Then decision logic template

Every area declaration should be accompanied by a completed reasoning chain. The following template is the minimum required documentation.

Field	Description	Example (Scenario A)
Governing hazard	The physical phenomenon driving the exclusion area	Lunar dust from ice extraction
Production rate	Measured or estimated hazard output, with unit	500 kg/hr (engineering estimate)
Confidence level	Stated uncertainty bracket, with rationale	Low (±50%); no lunar mission validation
Mitigation	Physical hazard reduction measures in place	None at scenario start
Core radius computed	Output of the framework formula, with parameters shown	13.7 km via dust mode, 500 kg/hr, Low, None
Area multipliers used	Buffer and coordination multipliers	Buffer 2.5× (34.3 km), Coordination 5× (68.5 km)
Assumptions	Key assumptions underlying the computation	Omnidirectional plume assumed; terrain shielding not modelled
Iteration history	Prior radius declarations, and what changed	Initial claim 50 km (v0); revised to 13.7 km after framework application (v1)
Review trigger	Conditions that require recomputation	Production rate changes by more than 20%, or mission validation data becomes available
Review period	Maximum time before mandatory recomputation	18 months recommended

5.3 Lunar Ledger integration

URL deep-link (implemented)

The framework accepts Lunar Ledger mission context via URL parameters, enabling the Ledger to deep-link into the tool with coordinates pre-populated:

```
https://aaronmac24.github.io/lunar-radius-framework
  ?lat=[selenographic_lat]&lon=[selenographic_lon]
  &site=[mission_name]&mission=[COSPAR_ID]&org=[operator]&status=[mission_status]
```

COSPAR refers to the Committee on Space Research, whose international designator is used as the mission identifier.

Proposed write-back schema (pending API confirmation)

```
PATCH /api/missions/{id}/operational-radius
{
  "operational_radius_km": 13.7,
  "dla_zones": { "core_km": 13.7, "buffer_km": 34.3, "coordination_km": 68.5 },
  "dla_inputs": {
    "hazard_type": "dust",
    "dust_rate_kg_hr": 500,
    "confidence": "Low (±50%)",
    "mitigation": "none",
    "framework_version": "0.6"
  },
  "computed_at": "2026-07-22T00:00:00Z"
}
```

6. Known Limitations and Open Questions

These limitations are documented not as failures but as the explicit boundary conditions of the current deliverable. They define the work required to move from a proof-of-concept tool to a regulatory instrument.

6.1 Formula calibration

Neither the leading coefficient of 0.5 nor the square-root scaling has been validated against lunar mission data. They produce kilometre-scale outputs consistent with ICES-2023-120 literature values, but mission operators may contest them with proprietary models. The exponent in particular is a provisional choice rather than a fitted value, and a calibration against real descent data may well shift it.

The calibration path runs through Intuitive Machines' Nova-C descent data, JAXA's Smart Lander for Investigating Moon (SLIM) landing measurements, and future Artemis surface operations. Treat the framework's formula as provisional until at least one peer-reviewed calibration is published.

Manual mode ratios, such as MW to km for thermal output, are entirely operator-defined. The framework enforces transparency of the ratio but cannot validate whether the ratio is proportionate. Peer review or COPUOS validation of reference ratios is needed.

6.2 Plume asymmetry

The framework assumes omnidirectional plume dispersion. Real lander plumes are shaped by descent trajectory, terrain, regolith composition, engine thrust, and cut-off altitude. A 50 km downrange risk profile may coexist with a 2 km crossrange profile.

An asymmetric hazard cone model, defined by approach vector and terrain, would produce more accurate area geometry. This is the next major technical development for the computation layer.

6.3 Temporal area bounding

Areas have no expiry in the current implementation. A 5 km core area claimed in 2029 and held until 2049 functions as de facto appropriation, which is the very problem the framework is designed to prevent.

Time-bound review triggers should be built into the GeoJSON metadata schema, and the Lunar Ledger should flag areas that have exceeded their declared review period without a recomputation event.

The framework currently has no mechanism for areas to shrink as confidence improves — for example, an initial Low confidence area that should contract once mission data validates a smaller radius. This is an important governance feature. Areas should be designed to shrink, not expand, over time.

6.4 Multi-operator conflict detection

The framework computes one operator's areas in isolation. It does not yet detect overlaps between two operators' declared areas.

The planned development is a two-operator input mode, where both operators' site coordinates and hazard parameters are entered simultaneously and the tool computes whether their areas overlap, and in which ring.

6.5 Enforcement

The framework establishes what a proportionate area should be. It does not enforce it. If an operator declares a 13.7 km area but operates as though it were 50 km, the framework has no mechanism to flag this.

Enforcement requires Lunar Ledger transparency, with operators publishing GeoJSON area declarations, and third-party monitoring. Both sit outside the framework's scope, but they are the natural next layer of the governance stack.

6.6 Political trust

ILRS-aligned states may distrust the framework if they perceive it as designed by or for Artemis Accords states.

As mitigation, Open Lunar Foundation would like to pursue co-development or co-validation with non-Artemis technical experts — the China National Space Administration (CNSA), the Indian Space Research Organisation (ISRO), or academic partners in ILRS states — to establish the framework's neutrality as a technical instrument.

6.7 Novel equipment and the experimental pathway

If an operator uses equipment with no historical analogue, such as a new propulsion type or a novel extraction method, no prior scenario documentation can serve as a reference. The framework's manual mode can still compute an area, but the ratio will be entirely novel.

This requires an experimental pathway protocol, under which operators of novel equipment submit their proposed ratios for peer review before area declaration, with a mandatory Unknown confidence level until the ratio is validated.

7. Stakeholder Interview Synthesis

The following synthesises findings from completed interviews. These insights directly informed scenario parameter choices and the open questions documented in Section 6.

7.1 Cross-cutting themes

Theme	Finding	Framework implication
Landing events dominate	All stakeholders identified lander plume events, rather than ongoing surface activity, as the primary coordination pressure. A single landing deposits roughly 43 times one ambient dust cycle.	Dust mode should eventually be parameterised by lander class and descent profile, not just production rate.
Data scarcity is universal	No operator had validated lunar dust production estimates. All operated from engineering models.	Low or Unknown confidence should be the default starting assumption for all near-term operators.

Theme	Finding	Framework implication
Temporal bounding is critical	Multiple stakeholders flagged area persistence as a governance risk, but temporal bounds create an incentive to claim short durations.	Review triggers tied to operational milestones, rather than calendar time, may be more resistant to gaming.
Post-mission data has high value	Stakeholders consistently valued a mechanism for retrospective measurement submission.	The Lunar Ledger should include a post-mission data submission pathway that triggers area recomputation.
Activity heat maps are valued	Multiple stakeholders independently requested a visualisation showing undisturbed against active lunar surface areas.	GeoJSON layer accumulation in the Ledger map view would produce this naturally as operators submit declarations.
Virgin regolith access	Any surface disturbance renders regolith unminable for helium-3 extraction, because the isotopes scatter. Virgin regolith access is a primary operational constraint. (Magna Petra)	For resource extraction operators, the coordination area has real economic stakes, not just safety stakes. This strengthens the governance case.
Safety transparency framing	The framework was framed around safety record transparency, by analogy with automotive safety ratings. Operators who publish decision logic build market credibility. (Blue Origin)	Public Lunar Ledger submission of If/Then documentation is a market incentive, not only a governance obligation.
Satellite disposal areas	Orbital debris re-entry corridors intersecting with surface operations were surfaced as a novel use case. (Volta Space)	Manual hazard mode can handle this, but it requires an impact debris ratio derived from trajectory modelling.

8. Simulation Tool Requirements

This section defines the requirements for integrating the Lunar Radius Framework with Vic Paulson's lunar surface simulation, Lunar Overlap, and for future computational simulation development.

8.1 Current integration status

Hook	Description	Status
SAFETY_RADIUS (primary)	DLA buffers.json replaces hardcoded pixel values in App.jsx for the pad, solar, habitat, and rover asset classes	Implemented; see SIMULATOR_PATCH.md

Hook	Description	Status
Governance regime presets	physOverrides bundles for Artemis Accords, ILRS, no-coordination, and Antarctic models	Infrastructure exists; bundles not yet defined
crater.quality field	PSR ice concentration per crater; currently defaults to 0.5 in extractCraters()	Hook exists; data not yet sourced
Rapporteur debrief prompts	Five structured prompts fired at turn-end, for stated-against-revealed preference capture	CSV and JSON export functional; prompts not yet wired
Map layer overlays	SLOPE.jpg, ALTITUDE.jpg, and EARTHVIS.jpg in public/; 700×700 greyscale JPGs needed	Placeholder files needed; data not yet generated

SAFETY_RADIUS is retained as the existing code identifier in the simulator, and is not a term used in the governance text of this paper.

8.2 Future computational simulation requirements

The following requirements are defined for any future team building a higher-fidelity simulation layer on this framework.

- The simulation must accept the framework's GeoJSON output as an area input layer, without requiring re-entry of parameters.
- Area overlaps between multiple operators must be detected and flagged automatically, with the specific ring-type of the overlap identified: core-on-core, buffer-on-core, or coordination-on-coordination.
- The simulation must support governance regime switching mid-run, to test how obligations change under different frameworks.
- Temporal area evolution should be modellable: areas should shrink as confidence improves, and expand as hazard conditions change.
- The simulation should include a rapporteur capture layer. After each operator turn, the five debrief prompts defined in the handoff document should be logged alongside move data, for stated-against-revealed preference analysis.
- Crater quality, meaning PSR ice concentration, should be sourced from the Lunar Orbiter Laser Altimeter (LOLA), the Diviner Lunar Radiometer Experiment, Korea Pathfinder Lunar Orbiter (KPLO) ShadowCam, and forthcoming datasets, then fed into the simulation via the GeoJSON pipeline rather than hardcoded.

9. Repository Structure and Source Files

The following describes the file organisation of the deliverable package and GitHub repository, at https://github.com/openlunar-dev/designated-lunar-areas-groundrules.

9.1 Repository contents

File or folder	Description
index.html	Application shell and markup. Open directly in a browser, or serve with python -m http.server 8000.
style.css	Dark-theme stylesheet. Fonts: Syne for display, Space Mono for data. No preprocessor required.
framework.js	All computation and interface logic: two input modes, GeoJSON builder, buffers.json builder, URL parameter parser, and Ledger banner. No dependencies.
SIMULATOR_PATCH.md	One-time instructions for integrating buffers.json into App.jsx in the Lunar Overlap simulator. Two edits required.
README.md	Repository documentation. Includes the live tool link, formula notes, source table, and roadmap.
docs/OLF_IfThen_Toolkit_Final_Deliverable.docx	This document, completing the fellowship final deliverable.
scenarios/scenario_a_shackleton.geojson	Pre-computed GeoJSON for Scenario A: Shackleton Crater rim, 500 kg/hr dust, Low confidence, no mitigation.
scenarios/scenario_b_power_station.geojson	Pre-computed GeoJSON for the Scenario B thermal layer: 750 MW, Medium confidence, no mitigation.
scenarios/scenario_a_ledger_template.json	Lunar Ledger submission template for Scenario A, structured per Section 5.2.

9.2 Running the tool locally

1. Clone or download the repository.
2. Open index.html directly in a browser, or serve it locally with python -m http.server 8000 and open http://localhost:8000.

No installation, no build step, and no dependencies.

10. References

Source	Citation
Outer Space Treaty	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies. United Nations, 1967.
Artemis Accords	NASA. Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes. 2020.
ILRS Guide	China National Space Administration and Roscosmos. International Lunar Research Station Guide for Partnership V1.0. 2021.
Lander plume deposition	ICES-2023-120. Texas Tech University. 52nd International Conference on Environmental Systems, 2023.
DLA three-ring framework	Tiballi, C. OLF Field Guide. Open Lunar Foundation, September 2025.
Ambient dust accumulation	Li et al. Chang'E-3 observations, Mare Imbrium. Journal of Geophysical Research: Planets, 2019.
Antarctic Treaty analogy	Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol), Article 7. 1991.
Commons governance	Ostrom, E. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, 1990.
This framework	Mackey, A. Lunar Radius Framework (v0.6). 2026. https://github.com/openlunar-dev/designated-lunar-areas-groundrules