

Supplementary Material: Compact Exhaust-Dilution Duct and Conditional Infrared Comparison for the MARID Leaf-Vein Hydrogen UAV

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This document supplements the manuscript “A Leaf-Vein Hydrogen Spar Architecture for Cryogenic Fuel Conditioning and Distributed Waste-Heat Rejection: Toward Low Infrared Contrast in a Long-Endurance UAV,” and expands its Sections III.G and IV.H.

1 Scope

This document evaluates MARID with its compact dilution duct and original airframe, as well as an enlarged straight-radiator installation and a concealed bent-radiator installation. The optical calculation explicitly assumes the visible housing, intake, and outlet.

The modeled daytime gross masses are 204.1 kg for a compact duct installation for MARID, 251.5 kg for the straight radiator, and 273.8 kg for the concealed bent alternative. These mass figures result from a weight spiral reconvergence (accounting for loaded hydrogen, resized tanks, and the fuselage). MARID is 47.4 and 69.7 kg lighter under these installation assumptions. The image ordering also depends on the view angle, background, and optics.

The installations retain the same 48-hour mission, payload and flight condition, with a common outlet-temperature rise limit of 2.90 K and bulk and inner-wall saturation limits of 0.98. Each aircraft’s mass, power demand and heat-rejection duty are reconverged.

Table 1 compares three measures of image contrast relative to the background. Maximum pixel contrast is the strongest local departure, whether brighter or darker. Total absolute contrast sums these departures across the image, weighted by pixel area, without cancellation. Net contrast magnitude takes the magnitude of the signed sum, allowing bright and dark regions to cancel. Lower contrast means a closer background match under the chosen measure, not simply a colder aircraft; cancellation can leave a small net value despite strong local contrasts. An entry of 14/16 means MARID has the lower value in 14 of the 16 scenes.

Table 1: Scenes, out of 16 (day and night, two bands, four views), in which compact MARID has the lower value of each metric against each radiator installation, for the five cameras of Table 4. These counts describe the selected scenes; they are not weighted by mission exposure or interpreted as detection probabilities.

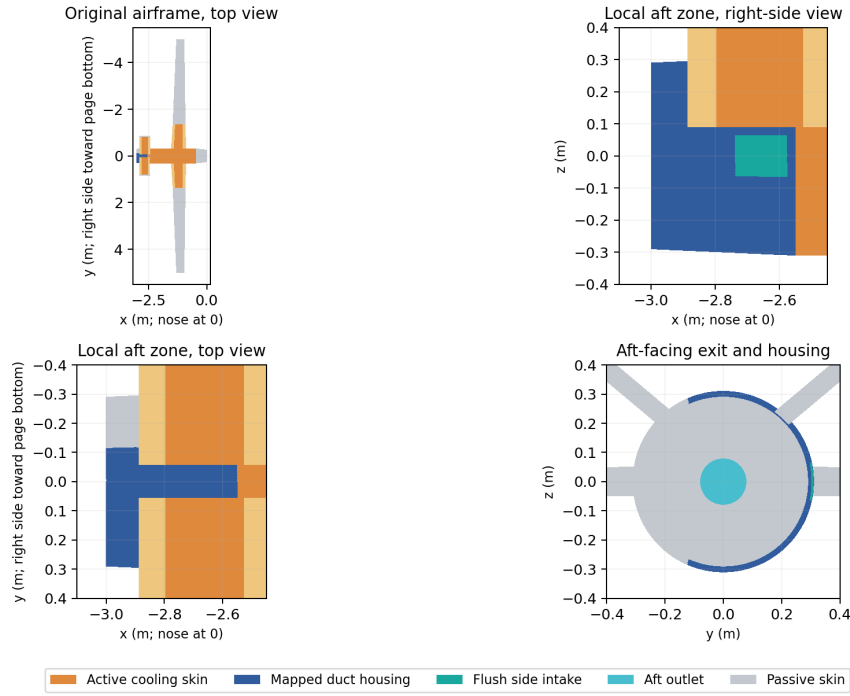
Camera	vs. straight radiator			vs. concealed bent radiator		
	Maximum pixel contrast	Total absolute contrast	Net contrast magnitude	Maximum pixel contrast	Total absolute contrast	Net contrast magnitude
Baseline	11/16	14/16	14/16	10/16	15/16	14/16
2× focal, $f/1$	11/16	15/16	14/16	9/16	15/16	14/16
4× focal, $f/1$	9/16	14/16	14/16	6/16	14/16	14/16
2× focal, fixed aperture	11/16	15/16	14/16	10/16	15/16	14/16
4× focal, fixed aperture	11/16	15/16	14/16	9/16	15/16	14/16

2 Installations and aircraft

Table 2: Aircraft mass and duct metrics for the three installations, separately converged day and night 48 h aircraft at 50 % ambient relative humidity (liquid reference). Radiator cases carry their prescribed 3 m internal routes and enlarged bodies; compact MARID keeps the original 0.62 m body.

Quantity	Compact MARID		Straight radiator		Concealed bent radiator	
	Day	Night	Day	Night	Day	Night
Gross mass, kg	204.1	204.1	251.5	251.5	273.8	273.9
Loaded hydrogen, kg	12.36	12.35	21.09	21.09	25.34	25.34
Dry tanks, kg	18.94	18.93	29.07	29.07	33.74	33.74
Body diameter, m	0.62	0.62	1.10	1.10	1.21	1.21
Duct diameter, mm	163.4	163.4	440.9	440.9	514.3	514.3
Thermal route length, m	1.004	1.004	3.000	3.000	3.000	3.000
Core duty, kW	—	—	7.24	7.24	8.60	8.60
Cathode exhaust sensible, W	449	449	766	766	921	921
Loop rejection, kW	4.473	4.468	7.240	7.240	8.602	8.602
Captured air, kg s^{-1}	0.372	0.372	3.214	3.214	3.933	3.934
Added drag, N	4.8	4.8	52.0	52.0	74.9	74.9
Outlet rise, K	1.51	1.44	2.76	2.69	2.74	2.68
Max. inner-wall saturation S_w	0.849	0.947	0.506	0.565	0.497	0.558

Compact MARID: assumed optical placement, not CAD or a routed installation



Thermal centerline 1.004 m; housing mapped by equal area onto the passive aft cone (stations 2.55–3.00 m). Inlet and route unverified. Top views: right side toward page bottom.

Figure 1: Conceptual compact placement used for the optical calculation: (a) original airframe, top view; (b) local aft zone, right-side view; (c) local aft zone, top view; (d) aft-facing exit and housing. Top views are drawn with the right side toward the bottom of the page. The 1.004 m thermal route's housing is mapped by equal area onto the passive aft cone between fuselage stations 2.55 and 3.00 m; an assumed fixture, not CAD.

3 Thermal states, humidity and numerical resolution

Table 3: Temperature, humidity and numerical-resolution inputs of the compact duct calculation.

Quantity	Value
Flight point	ISA 3,000 m, 33.35 m s^{-1} TAS; ambient 268.65 K (-4.5°C)
Ambient relative humidity	50 %, referenced to liquid water; ambient vapor enters the dilution air and the cathode
Saturation reference	liquid water at and above 0°C , ice below (Murphy and Koop, 2005)
Design screens	inner-wall and bulk saturation ratio ≤ 0.98 ; outlet rise $\leq 2.90 \text{ K}$
Duct model	sensible gas, liner, housing and surroundings balance; cross-sectionally mixed flow; no phase change solved
Compact duct	163.4 mm bore; 0.20 m inlet + 0.654 m mixing (four diameters) + 0.15 m outlet = 1.004 m
Primary mesh	0.5 mm first cell downstream of exhaust injection
Night wall saturation, mesh ladder	0.94721 / 0.94757 / 0.94776 at 0.5 / 0.25 / 0.125 mm; last change 0.00019; margin 0.39 K to the screen
Day wall saturation, finest mesh	0.84975
Internal coefficient probe	$40 \rightarrow 20 \text{ W m}^{-2}\text{K}^{-1}$ at fixed aircraft load and a 0.125 mm first cell: night wall ratio 0.96985, below the 0.98 screen
Day and night	separately converged steady 48 h aircraft, not an integrated diurnal mission

4 Optical configurations and scenes

Table 4: The five ideal cameras (fixed D : the baseline aperture retained at the longer focal lengths) and the four scenes.

	Camera				
	Baseline	2×, $f/1$	4×, $f/1$	2×, fixed D	4×, fixed D
<i>3–5 μm (MWIR): 15 μm pixels; PSF at 4 μm</i>					
Focal length, mm	100	200	400	200	400
Aperture, mm	100	200	400	100	100
f -number	1	1	1	2	4
Pixel at 6 km / 1 km, m	0.90 / 0.15	0.45 / 0.075	0.225 / 0.0375	0.45 / 0.075	0.225 / 0.0375
<i>8–12 μm (LWIR): 12 μm pixels; PSF at 10 μm</i>					
Focal length, mm	50	100	200	100	200
Aperture, mm	50	100	200	50	50
f -number	1	1	1	2	4
Pixel at 6 km / 1 km, m	1.44 / 0.24	0.72 / 0.12	0.36 / 0.06	0.72 / 0.12	0.36 / 0.06
<i>Scenes (US standard atmosphere; sources held at their thermal states across backgrounds)</i>					
From below, clear sky	elevation -30° , azimuth 135° , range 6 km				
From above, terrain	elevation $+30^\circ$, azimuth 135° , range 6 km; terrain 288 K				
From above, cloud	elevation $+30^\circ$, azimuth 135° , range 6 km; cloud top at 2.8 km				
Aft	elevation 0° , azimuth 180° , range 1 km; horizon: air-temperature blackbody				
Ideal optics: Airy PSF truncated at $12\lambda R/D$, exact detector-area integration, zero registration phase, no noise or jitter.					
Native scene sampling	7.5 / 1.25 mm (MWIR) and 20 / 2.5 mm (LWIR) at 6 / 1 km.				

5 Image results

Table 5: Scenes, out of 8 per band, in which compact MARID has the lower peak absolute contrast against each radiator installation.

Camera	vs. straight radiator		vs. concealed bent radiator	
	3–5 μm	8–12 μm	3–5 μm	8–12 μm
Baseline	4/8	7/8	3/8	7/8
$2\times$ focal, $f/1$	4/8	7/8	3/8	6/8
$4\times$ focal, $f/1$	4/8	5/8	2/8	4/8
$2\times$ focal, fixed aperture	4/8	7/8	3/8	7/8
$4\times$ focal, fixed aperture	4/8	7/8	2/8	7/8

Table 6: Peak absolute contrast, $\text{W m}^{-2} \text{sr}^{-1}$, for all 240 camera images: 16 scenes (state, band, view) by five cameras, three installations. Cameras: B baseline; 2F1, 4F1 twice and four times the focal length at $f/1$; 2D, 4D the same focal lengths at the baseline aperture. Views: below = from below against clear sky; terrain and cloud = from above against 288K terrain or a 2.8km cloud top (6 km); aft = from behind at 1 km.

Cam.	State	Band, μm	View	MARID	Straight	Bent
B	day	3–5	below	0.26	0.229	0.232
B	day	3–5	terrain	0.109	0.254	0.259
B	day	3–5	cloud	0.168	0.116	0.119
B	day	3–5	aft	0.0655	3.420	0.0484
B	day	8–12	below	7.665	9.332	9.785
B	day	8–12	terrain	2.199	4.233	4.419
B	day	8–12	cloud	0.665	0.362	0.35
B	day	8–12	aft	0.0627	22.63	0.264
B	night	3–5	below	0.231	0.204	0.206
B	night	3–5	terrain	0.156	0.277	0.278
B	night	3–5	cloud	0.0736	0.0116	0.0116
B	night	3–5	aft	0.00623	3.413	0.0174
B	night	8–12	below	7.494	9.167	9.594
B	night	8–12	terrain	2.534	4.640	4.836
B	night	8–12	cloud	0.329	0.769	0.767
B	night	8–12	aft	0.55	22.45	0.606
2F1	day	3–5	below	0.311	0.246	0.244
2F1	day	3–5	terrain	0.35	0.454	0.461
2F1	day	3–5	cloud	0.275	0.177	0.186
2F1	day	3–5	aft	0.116	3.527	0.071
2F1	day	8–12	below	13.45	13.78	14.12
2F1	day	8–12	terrain	3.921	6.746	6.838
2F1	day	8–12	cloud	1.542	0.736	0.697
2F1	day	8–12	aft	0.178	33.74	0.34
2F1	night	3–5	below	0.277	0.217	0.219
2F1	night	3–5	terrain	0.236	0.301	0.304
2F1	night	3–5	cloud	0.11	0.027	0.0249
2F1	night	3–5	aft	0.0114	3.520	0.0177
2F1	night	8–12	below	13.13	13.53	13.83
2F1	night	8–12	terrain	4.449	7.359	7.436
2F1	night	8–12	cloud	0.976	1.349	1.319
2F1	night	8–12	aft	0.655	33.66	0.637
4F1	day	3–5	below	0.344	0.251	0.258
4F1	day	3–5	terrain	0.461	0.474	0.476
4F1	day	3–5	cloud	0.332	0.21	0.211
4F1	day	3–5	aft	0.208	3.538	0.12
4F1	day	8–12	below	17.45	15.66	15.81
4F1	day	8–12	terrain	6.416	7.663	7.694
4F1	day	8–12	cloud	2.206	1.044	1.019
4F1	day	8–12	aft	0.319	35.84	0.358
4F1	night	3–5	below	0.308	0.225	0.225
4F1	night	3–5	terrain	0.303	0.315	0.317
4F1	night	3–5	cloud	0.13	0.034	0.0333
4F1	night	3–5	aft	0.0286	3.531	0.0177
4F1	night	8–12	below	17.01	15.37	15.47

Cam.	State	Band, μm	View	MARID	Straight	Bent
4F1	night	8–12	terrain	6.917	8.360	8.501
4F1	night	8–12	cloud	1.543	1.917	1.952
4F1	night	8–12	aft	0.788	35.78	0.723
2D	day	3–5	below	0.29	0.238	0.237
2D	day	3–5	terrain	0.306	0.425	0.436
2D	day	3–5	cloud	0.25	0.164	0.173
2D	day	3–5	aft	0.103	3.459	0.0658
2D	day	8–12	below	9.636	11.01	11.45
2D	day	8–12	terrain	3.206	5.286	5.467
2D	day	8–12	cloud	0.971	0.521	0.511
2D	day	8–12	aft	0.113	29.79	0.307
2D	night	3–5	below	0.258	0.211	0.209
2D	night	3–5	terrain	0.212	0.285	0.29
2D	night	3–5	cloud	0.101	0.0241	0.0224
2D	night	3–5	aft	0.01	3.452	0.0175
2D	night	8–12	below	9.413	10.82	11.23
2D	night	8–12	terrain	3.639	5.796	5.979
2D	night	8–12	cloud	0.546	1.031	1.024
2D	night	8–12	aft	0.573	29.68	0.611
4D	day	3–5	below	0.318	0.24	0.241
4D	day	3–5	terrain	0.367	0.437	0.442
4D	day	3–5	cloud	0.284	0.183	0.182
4D	day	3–5	aft	0.145	3.465	0.086
4D	day	8–12	below	10.22	11.72	12.14
4D	day	8–12	terrain	3.297	5.495	5.674
4D	day	8–12	cloud	1.066	0.571	0.562
4D	day	8–12	aft	0.127	31.08	0.312
4D	night	3–5	below	0.285	0.214	0.214
4D	night	3–5	terrain	0.251	0.295	0.294
4D	night	3–5	cloud	0.113	0.028	0.0282
4D	night	3–5	aft	0.0182	3.457	0.0175
4D	night	8–12	below	9.973	11.51	11.90
4D	night	8–12	terrain	3.734	6.010	6.192
4D	night	8–12	cloud	0.639	1.076	1.071
4D	night	8–12	aft	0.585	31.00	0.612

6 Interpretation

Under the prescribed installation assumptions, compact MARID has the lowest converged aircraft mass. Its infrared advantage depends on viewing direction, background and camera resolution; the bent radiator produces lower peak contrast in some scenes.

Against a clear sky, even passive skin produces infrared contrast. The relevant distinction is between the contrast already present without loop heating and the additional contribution of heat rejection. The passive-skin temperature reference illustrates this distinction, but does not quantify the radiometric penalty in every scene.

Figures 5 and 13 show almost nothing for the compact and concealed installations. Each figure shares one symmetric colour scale across its fifteen panels, and in the aft 3–5 μm scenes

that scale is set by the straight radiator’s exposed core, about 3.4 to $3.5 \text{ W m}^{-2} \text{ sr}^{-1}$ in every camera; the other two installations peak between 0.006 and $0.21 \text{ W m}^{-2} \text{ sr}^{-1}$, so their pixels fall within the near-white band. Two things keep them low: from directly aft the airframe presents only its end-on section, and near-ambient surfaces emit much less in the $3\text{--}5 \mu\text{m}$ band than in the $8\text{--}12 \mu\text{m}$ band. The $8\text{--}12 \mu\text{m}$ aft scenes (Figures 9 and 17) are dominated by the same core. In the from-below and from-above scenes, the exposed core no longer dominates the comparison.

These results compare conceptual installations and ideal-camera responses. They support further assessment of distributed skin rejection for MARID’s mission requirements, rather than a universal infrared ranking.

Camera images

Each figure below shows one scene; its title gives the time of day, the band, the view geometry and the atmosphere. Rows are the three installations with their day gross masses: compact MARID, the straight radiator and the concealed bent radiator. Columns are the five cameras of Table 4, from the reference optics on the left to four times the focal length at the fixed aperture on the right. Each panel is the camera image of the aircraft at the stated range, plotted in screen coordinates at the aircraft in metres, and shows the excess radiance of each pixel above the background, ΔL in $\text{W m}^{-2} \text{sr}^{-1}$: red is brighter than the background, blue darker, near-white is low contrast on that figure's scale. The colour scale is shared by the fifteen panels of a figure but differs between figures, so panels are comparable within a figure, not across figures; the peak $|\Delta L|$ printed above each panel is the absolute value, and it is what Tables 5 and 6 report. A small bright spot, as for the straight radiator seen from aft, is a hot exposed core; a panel that stays near-white has no pixel far from the background at that scale, which is not the same as being undetectable.

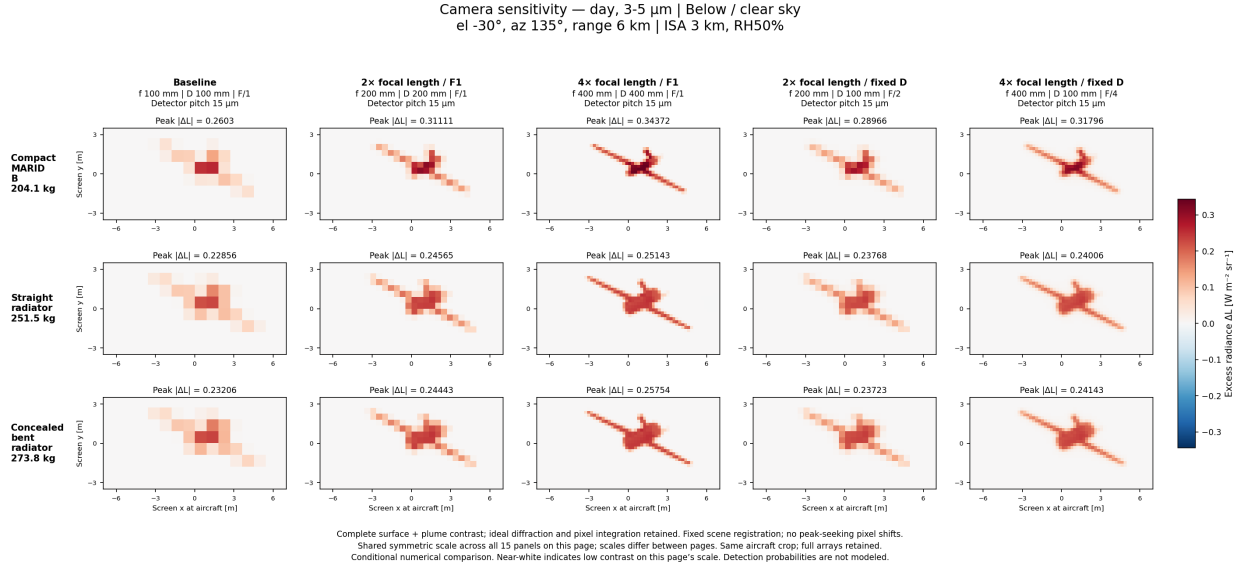


Figure 2: Day, $3\text{--}5\ \mu\text{m}$, from below against clear sky (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

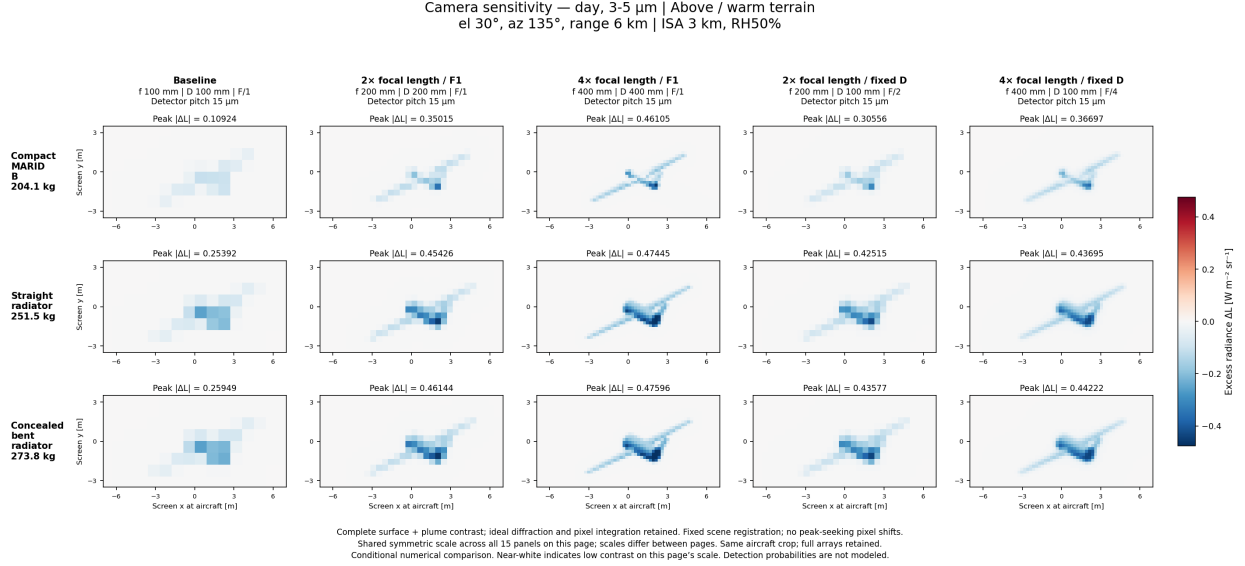


Figure 3: Day, 3–5 μm , from above against 288 K terrain (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

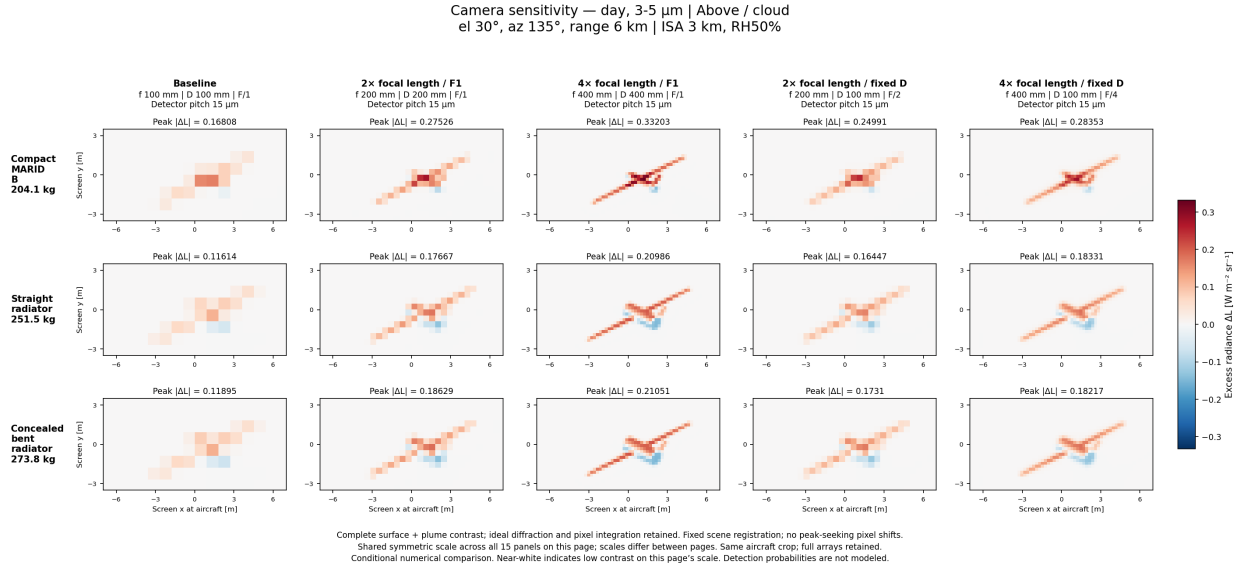


Figure 4: Day, 3–5 μm , from above against a 2.8 km cloud top (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

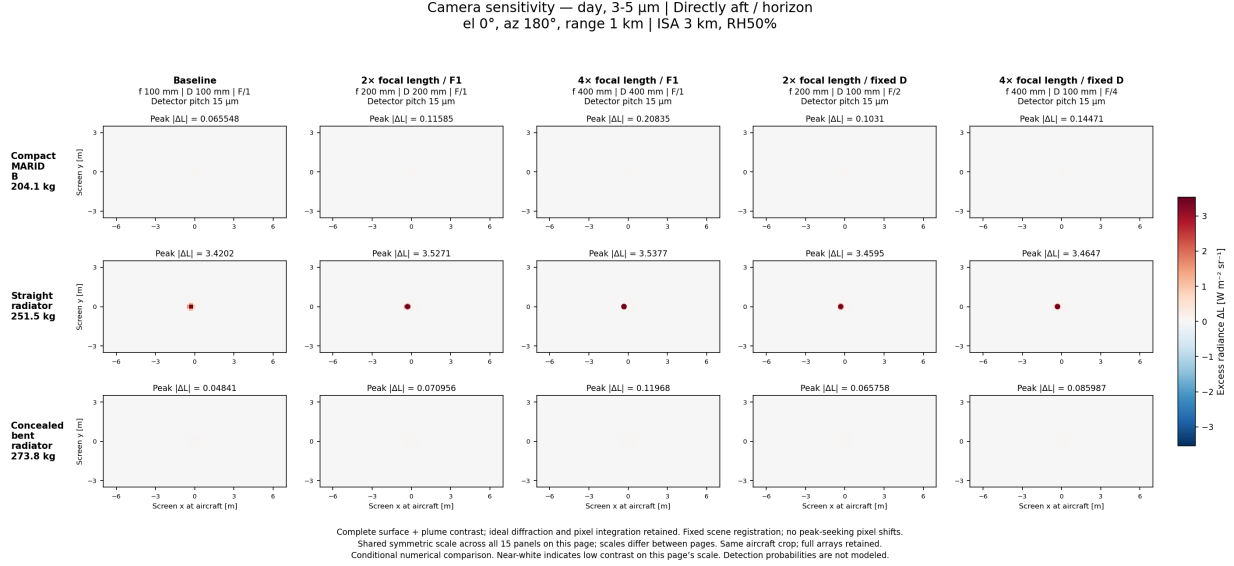


Figure 5: Day, 3–5 μm , from aft at 1 km: compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

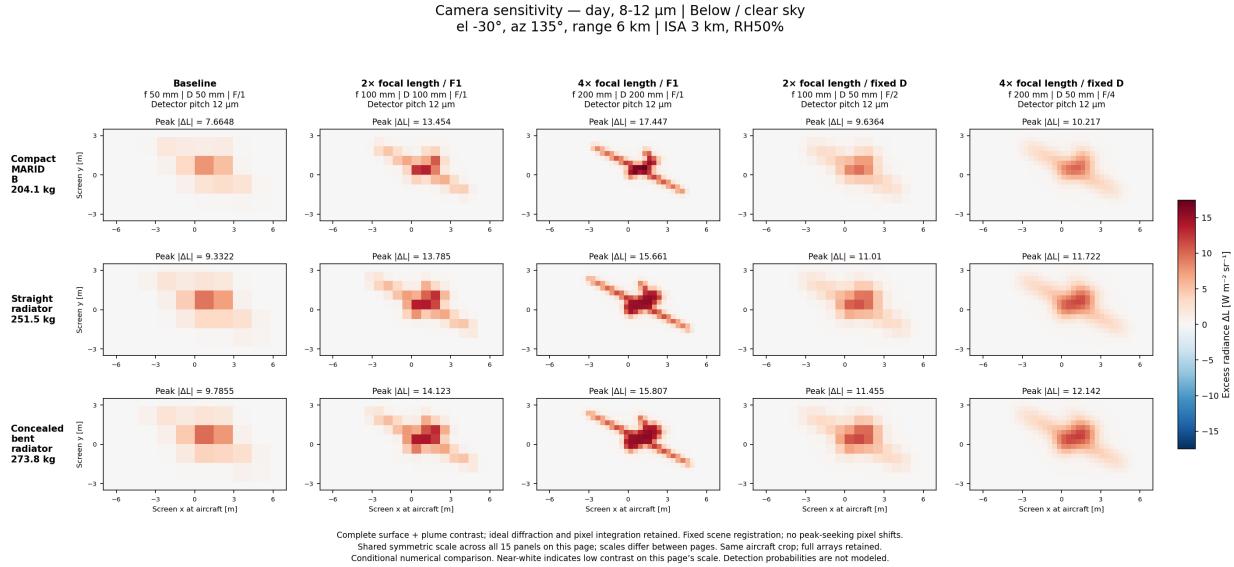


Figure 6: Day, 8–12 μm , from below against clear sky (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

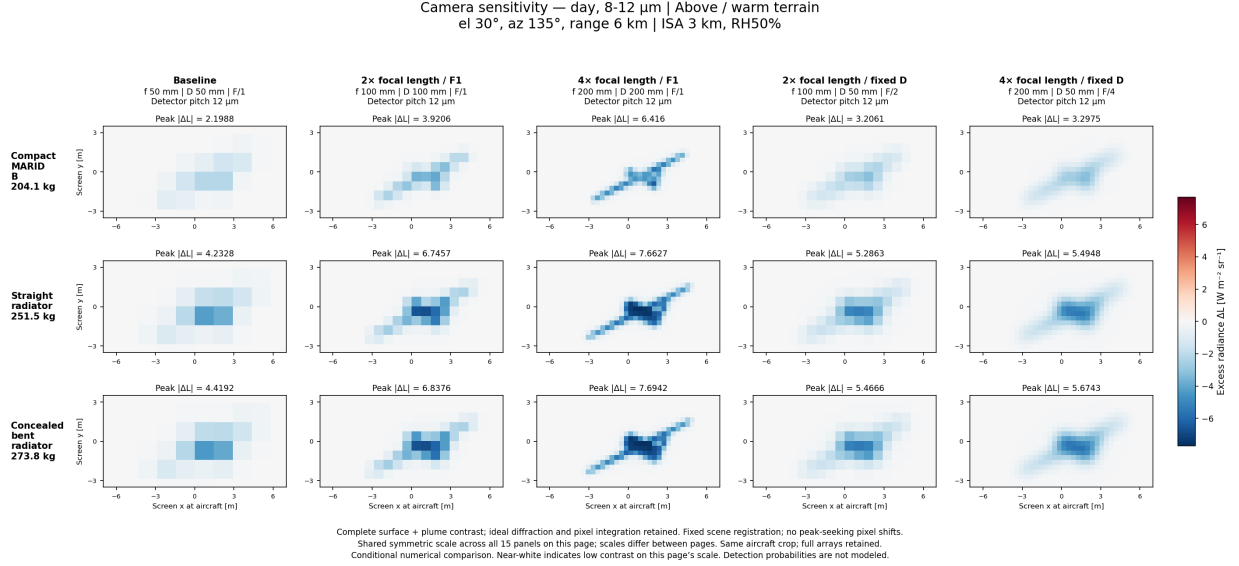


Figure 7: Day, 8–12 μm , from above against 288K terrain (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

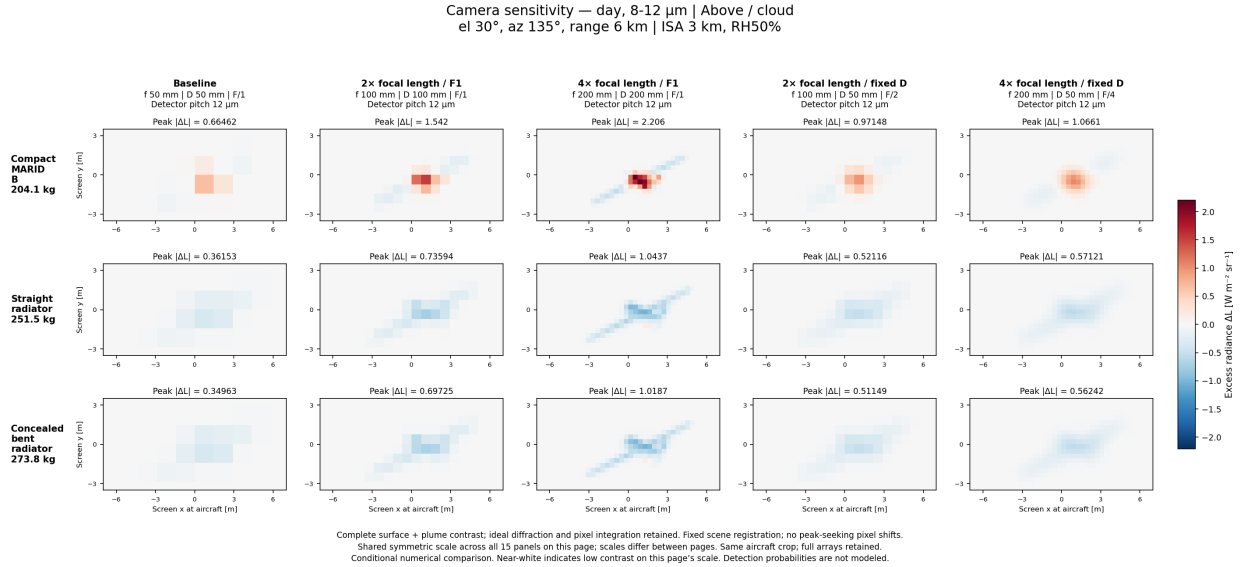


Figure 8: Day, 8–12 μm , from above against a 2.8 km cloud top (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

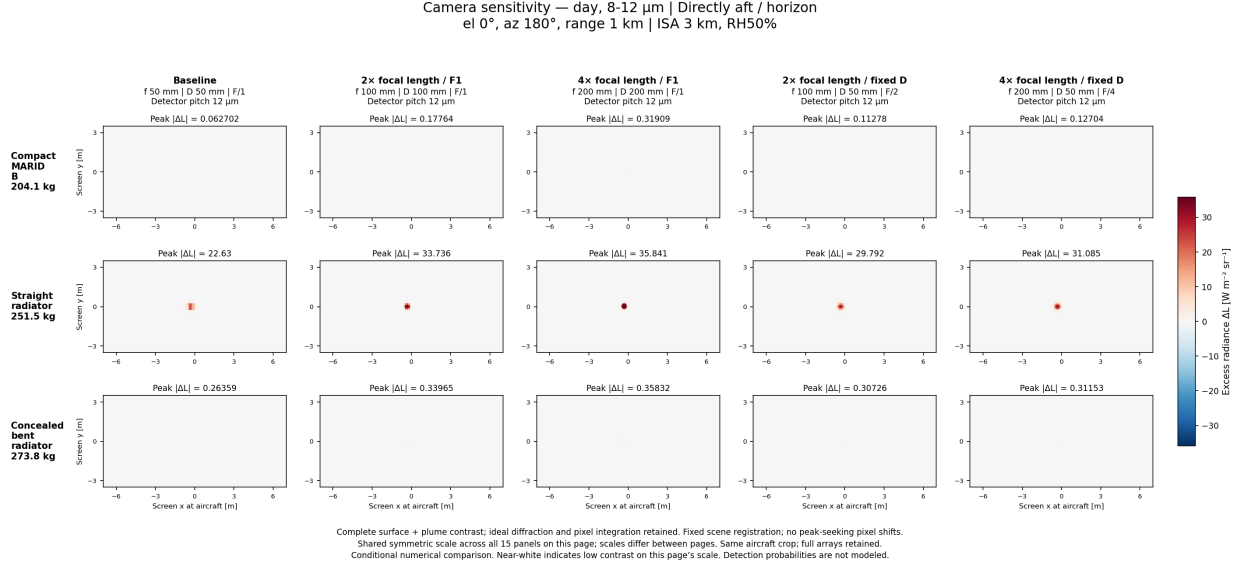


Figure 9: Day, 8–12 μm , from aft at 1 km: compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

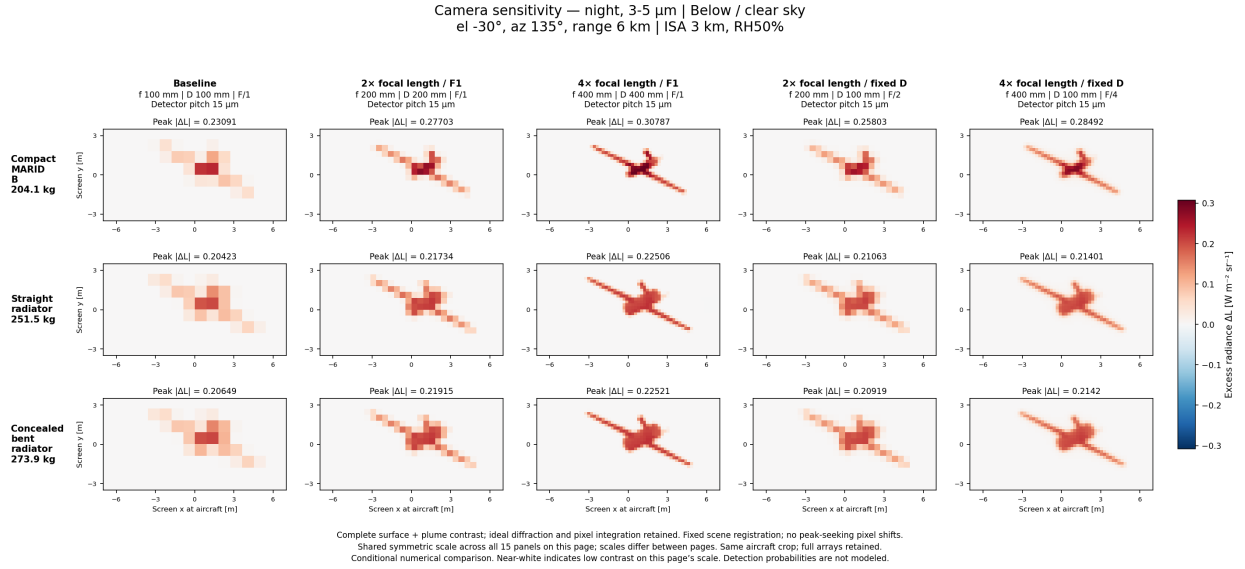


Figure 10: Night, 3–5 μm , from below against clear sky (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

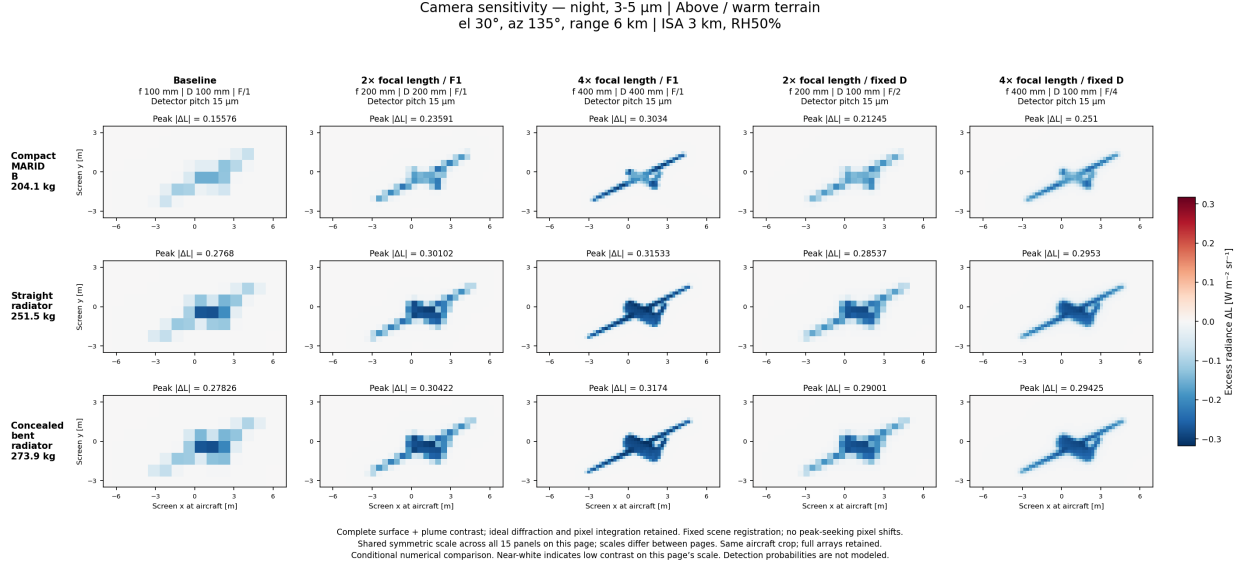


Figure 11: Night, 3–5 μm , from above against 288 K terrain (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

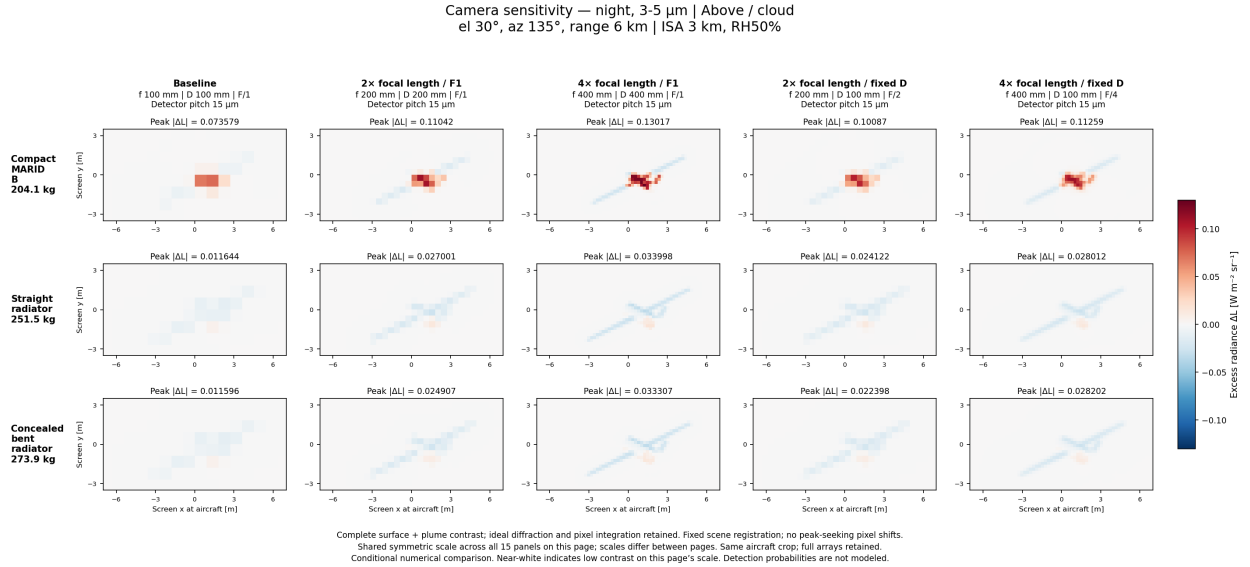


Figure 12: Night, 3–5 μm , from above against a 2.8 km cloud top (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

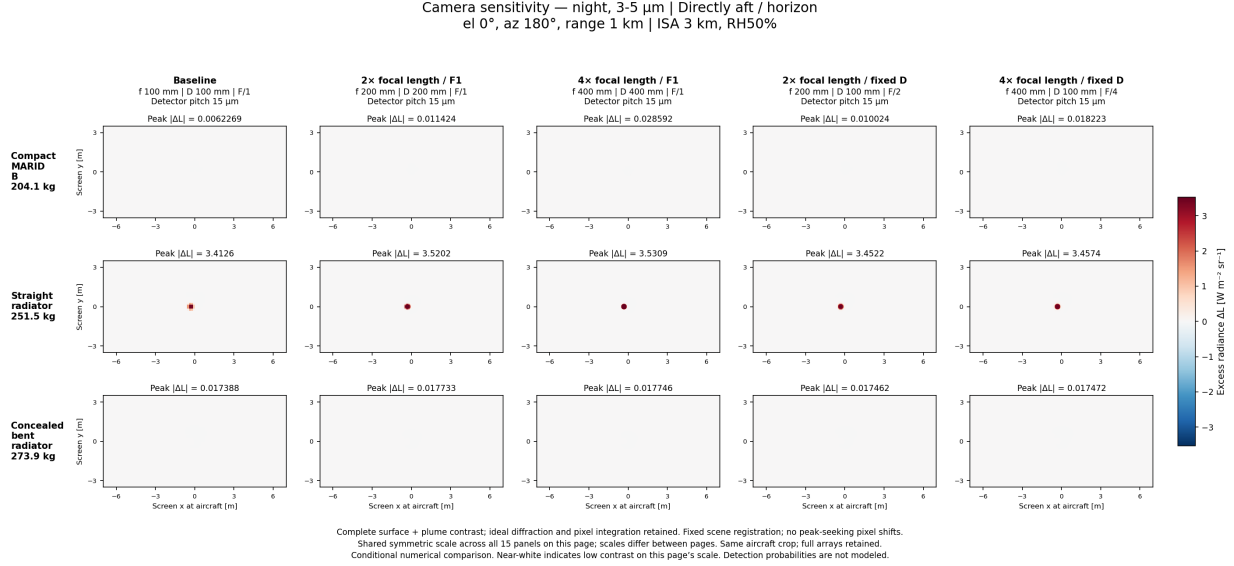


Figure 13: Night, 3–5 μm , from aft at 1 km: compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

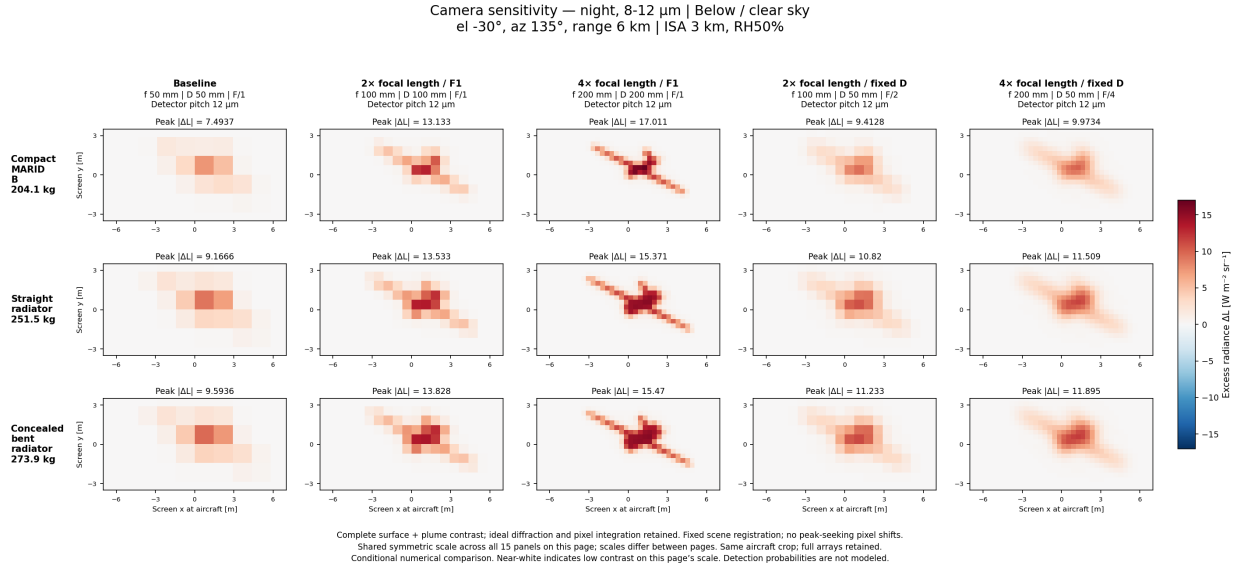


Figure 14: Night, 8–12 μm , from below against clear sky (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

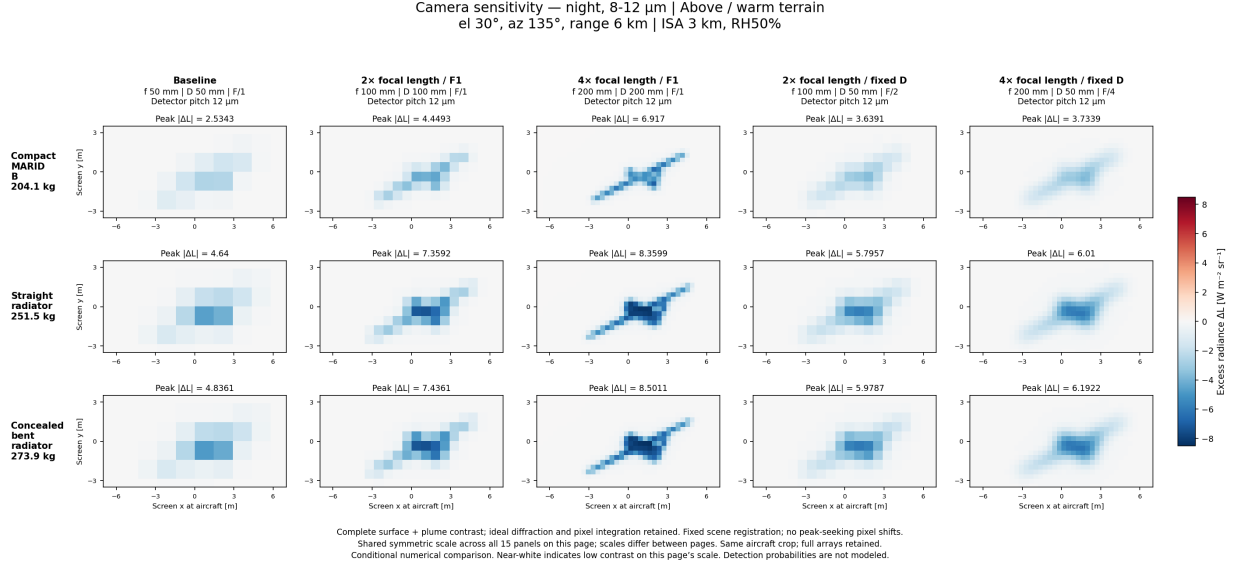


Figure 15: Night, 8–12 μm , from above against 288 K terrain (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

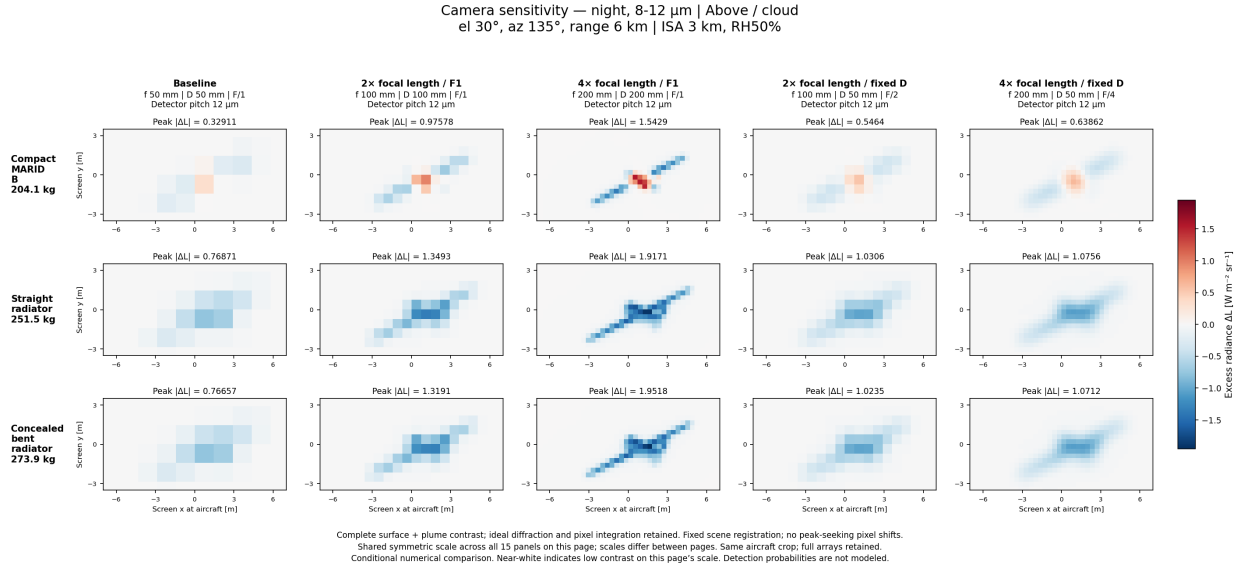


Figure 16: Night, 8–12 μm , from above against a 2.8 km cloud top (6 km): compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.

Camera sensitivity — night, 8–12 μm | Directly aft / horizon
el 0°, az 180°, range 1 km | ISA 3 km, RH50%

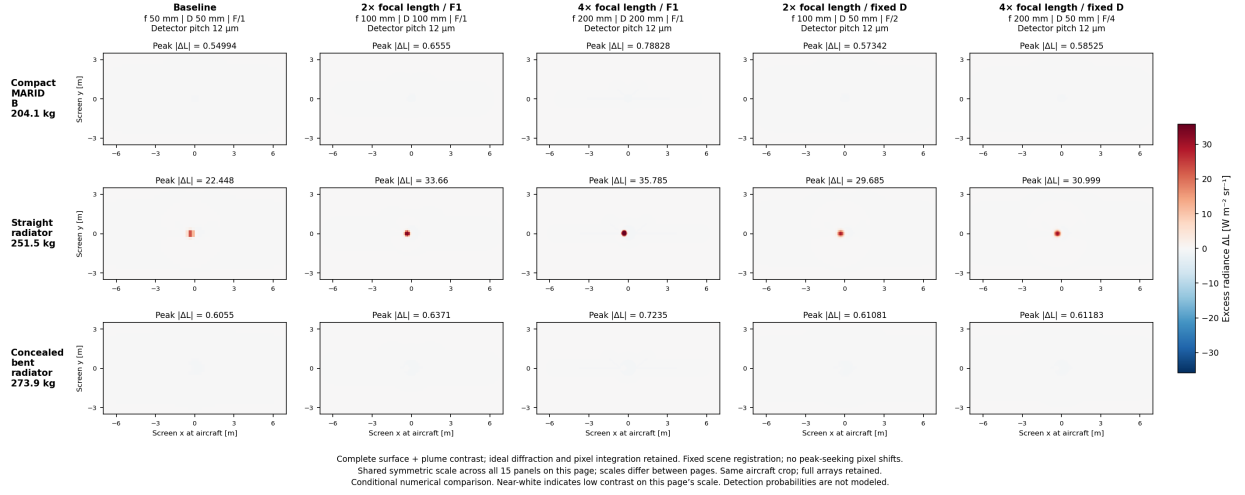


Figure 17: Night, 8–12 μm , from aft at 1 km: compact MARID, straight radiator and concealed bent radiator through the five cameras of Table 4.