AVT-371 Research Workshop on

"Materials and technologies for electro-optical camouflage"

Directional thermal infrared emissivity materials and materiel

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QINETIQ

Agenda

- Introduction
  - The thermal infrared threat
  - Field Deployable Electro Optic sensor (FDEOS) kits
  - The physics (and the problem) of thermal IR emissivity control
- Directional thermal IR emissivity
  - Materials
  - Modelling
  - Combat Identification case
- Summary & questions

Integrated survivability

- Peer REDFOR* likely to use layered ISTAR* to control and effect Fires
- BLUEFOR may counter layered ISTAR fire control with Integrated Survivability - a Layered Strategy
  - Layered Survivability - Sometimes called the "Survivability Onion"
- Electro-Optic (EO) Camouflage Concealment and Deception disrupts REDFOR OODA* loop at the first stage: degrading 'observation'
  - Reduces REDFOR combat efficiency & interrupts flow of 'kill chain'
- EO CCD is effective at several stages of Layered Survivability Strategy
  - Reducing probability or range of Detection, Recognition and Identification
  - Enables greater freedom of movement without being detected
    - Opens the battlespace to BLUEFOR manoeuvre
    - Increases Detection range over-match
  - Reducing signature can increase smoke/obscurant/countermeasure effectiveness

Layered Survivability

1. Don't be there
2. Don't be seen
3. Don't be acquired
4. Don't be hit
5. Don't be killed
6. Do get home

EO CCD assists 1-4
EO CCD assists 6 too

Peer REDFOR : A sovereign nation state with Armed Forces whose capabilities [technological, equipment, doctrinal, organisational] are equivalent or superior.
ISTAR: Intelligence Surveillance Target Acquisition and Reconnaissance
BLUEFOR : Own forces and allies
OODA : Observe, Orient, Decide, Act
EO CCD : Electro–Optic Camouflage, Concealment & Deception

‘Hemispherical’ thermal IR threat direction

ISTAR Imaging systems are deployed on UAVs, manned aircraft and other vehicles, and are also used by dismounts.

Eleron-3SV

Zastava

Takhion

Orlan-10

Granat-4

Forpost

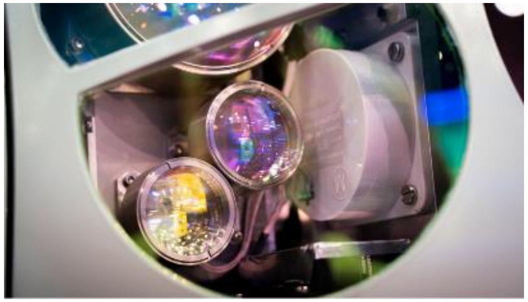
Forpost/Israeli optics (2014)

CHN TIR binoculars (2018)

Thermal IR threat evolution

Orlan 30 recce variant with Electro-Optic turret (Ukraine conflict 2022)

GOES-4 produced by NPP AME (RUS) for Forpost R: cooled MWIR WFOV and NFOV, low light TV, range finder & designator



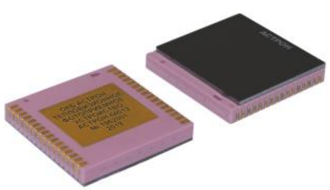
HTEB.461321.011 range finder & designator produced by Quantum Optics (RUS)

Thermal IR threat evolution

Left; Orlan 10 recovered in UKR in 2022, Right; close-up of TIR-only imaging pod on recovered Orlan 10

АСТРОН-64012

ТЕПЛОВИЗИОННЫЕ ДЕТЕКТОРЫ



Микроболометрический матричный детектор

- Технология микроболометров: VOx.
- Шаг матрицы: 12 мкм.
- Спектральный диапазон: 7–14 мкм.
- Чувствительность: ≤ 40 мК (@ f / 1,0; 50 Гц; 300 К).
- Разрешение детектора: 640 × 512.
- Частота кадров: ≤ 60 Гц.

7-14 мкм СПЕКТР | 12мкм ДЕТЕКТОР | 640*512 | КОРРЕКЦИЯ ПИКСЕЛЕЙ

Фотоприемное устройство АСТРОН-64012 дальнего инфракрасного (тепловизионного) спектра излучения изготовлено на основе матрицы микроболометров с малым шагом. Инфракрасные детекторы с шагом матрицы 12 мкм относятся к последним техническим достижениям в своем классе приборов.

ФПУ АСТРОН-64012 можно отнести к особо перспективным для применения в носимых тепловизионных системах, а также для применения на борту беспилотных летательных аппаратов. Малый геометрический размер матрицы позволяет существенно снизить массогабаритные характеристики оптической системы при сохранении высокого разрешения и чувствительности. Кроме этого, детектор обладает наименьшим энергопотреблением и весом в линейке наших приборов.

АСТРОН-640/75

ТЕПЛОВИЗИОННЫЕ МОДУЛИ С ОБЪЕКТИВОМ

Матричный неохлаждаемый модуль

- Детектор: МФПУ АСТРОН-64017.
- Шаг матрицы детектора: 17 мкм.
- Чувствительность детектора: < 60 мК.
- Чувствительность, температурный эквивалент шума модуля: < 55 мК с технологией снижения шума.
- Разрешение модуля: 640 × 480 (PAL).
- Частота кадров модуля: 25 Гц.
- Спектральный диапазон: 7–14 мкм.
- Автоматическая регулировка усиления.
- Цифровое улучшение деталей изображения.
- Автоматическое изменение динамического диапазона.
- Настройка параметров через пользовательское меню.
- Объектив: монокристалл германия f/F = 75/1,0.
- Серийное производство.

7-14 мкм СПЕКТР | 17мкм ДЕТЕКТОР | IP65 | 25 Гц | БЕЗ ШТОРКИ | ВЫХОД BT.656 | 640*480 | КОРРЕКЦИЯ ПИКСЕЛЕЙ | OSD НАСТРОЙКА

Тепловизионные неохлаждаемые модули АСТРОН-640/75 являются базовыми элементами для тепловизионных приборов и аппаратуры. Модули могут быть использованы при разработке и производстве оптико-электронных приборов с тепловизионным каналом разрешением 640 × 480 и углом поля зрения 8,3 × 6,2 градусов. Модуль включает ТВМ АСТРОН-640В17 и объектив АСТРОН-75Ф10. Дополнительную информацию можно получить в разделах с каталожными листами соответствующего модуля и объектива.

Модуль поставляется в полной заводской готовности. Завершающей стадией производства является калибровка тепловизионного модуля с конкретным объективом. Этим достигается наилучшее качество изображения в сравнении с применением модуля без калибровки под конкретный объектив. Особенно это актуально для объективов с длинным фокусом.

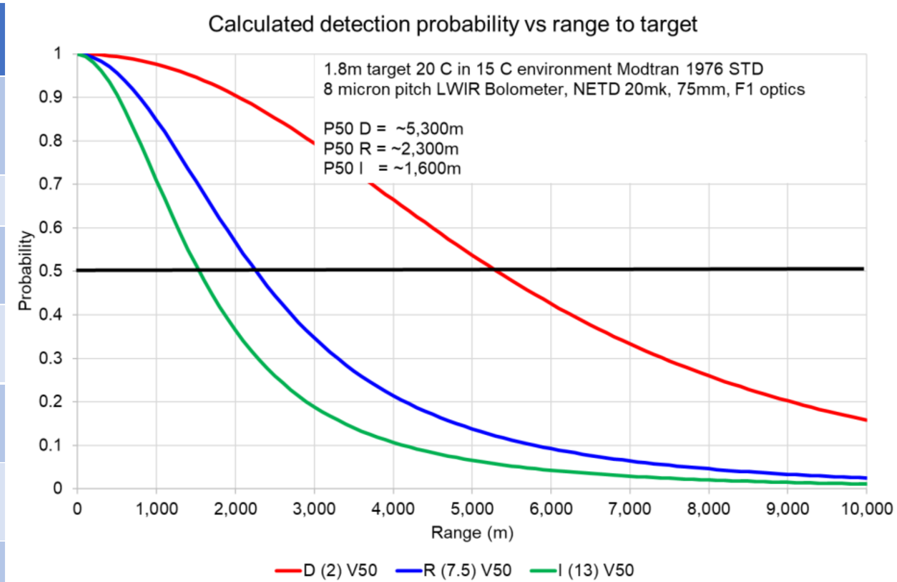
Интеграция модуля в корпус прибора производится через фланец с герметизирующей прокладкой. Параметры питания и выходные сигналы модуля по требованию заказчика могут быть изменены на параметры, указанные на странице «Таблица интерфейсных плат» в разделе «Тепловизионные модули». Производятся серийно.

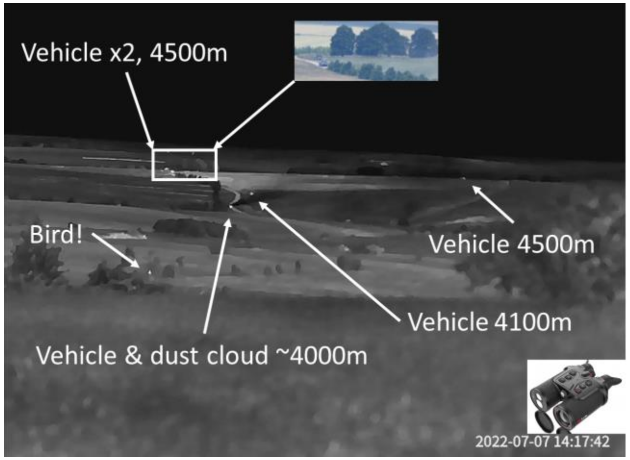
ГАБАРИТНЫЙ ЧЕРТЕЖ И РАЗМЕРЫ

Thermal IR threat evolution

Serial	Year	Chronology of known COTS CHN LWIR portable micro-bolometers			
0	2011	**Micro-bolometer array manufacturing established (Yantai, Shandong Province, CHN)**			
			Detection[1] (m)	Recognition (m)	Identification (m)
1	2013	Published: CHN 25 micron pitch, NETD 75mk, fl 40mm, F1 optics	1,200	500	300
2	2015	Published: CHN 17 micron pitch, NETD 50mk, fl 40mm, F1 optics	1,700	700	500
3	2018	CHN 518B: 17 micron pitch, NETD 50mk, fl 50mm, F1 optics	2,100	900	600
4	2021	CHN TN650: 12 micron pitch, NETD 30mk, fl 50mm, F1 optics	2,800	1,200	800
5	2022	CHN RAPTOR: 12 micron pitch, NETD 20mk, fl 50mm, F0.9 optics	2,900	1,250	850
6	2023	CHN: 12 micron pitch LWIR Bolometer, NETD 20mk, fl 75mm, F1 optics	4,300	1,800	1,200
7	2024?	CHN current fixed position product, potential to be Field Deployed: 8 micron pitch, NETD 20mk, fl 75mm, F1 optics	5,300	2,300	1,600

[1] Detection, Recognition and Identification of a man-sized object (1.8m) at 20+/-3° °C in a 15 +/-3°C environment calculated with NV-IPM using a MODTRAN standard atmosphere with no precipitation, clouds or aerosols.





FDEOS

- Field Deployable Electro-Optic Sensor (FDEOS) ‘kits’
  - Variants have been produced to help troops understand their EO signature & optimise counter surveillance control measures
  - Indigenous Russian Gen 2+ & Gen 3 Image Intensifier imaging sensors
  - Indigenous Chinese thermal IR imaging systems
  - Other imaging systems

The physics (and the problem) of thermal IR emissivity control

- Match the thermal IR radiance of the platform to the background viewed by the threat
  - Match actual surface temperature to background (conceal hot parts, insulation, solar heat rejection coatings etc. etc.)
  - Minimise remaining radiance contrast using thermal IR emissivity control

Planck

$$M_\lambda = \frac{2\pi c^2 h}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

Stefan-Boltzmann

$$M(\varepsilon)_{total} = \varepsilon_{total} \sigma T^4$$

Kirchhoff (opaque body)

$$\varepsilon_\lambda = \alpha_\lambda = 1 - R_\lambda$$

- Physics - 'easy' to solve
  - 'consider a uniform isothermal spherical body in an isothermal environment'
- Real world – much harder
  - No isothermal simple-shaped bodies or isothermal environments
  - Reducing thermal IR emissivity increases thermal IR reflections
  - Reflected thermal IR radiance can dominate signature
  - Ensure that reflections don't break your camouflage
- Options for controlling reflected IR radiance:
  - Specular – Diffuse surfaces
  - Directional surfaces – Control what is reflected in which direction

M = Excitance, λ = Wavelength, c = Speed of light, h = Planck's constant, k = Boltzmann constant, T = Temperature, ε = Emissivity, σ = Stefan- Boltzmann constant, α = Absorptivity, **R = Reflectivity**.

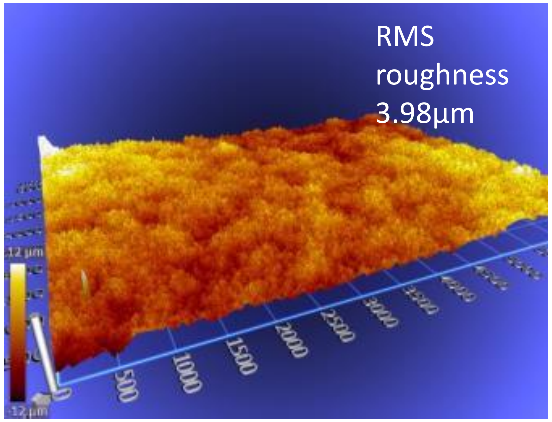
Directional thermal IR emissivity

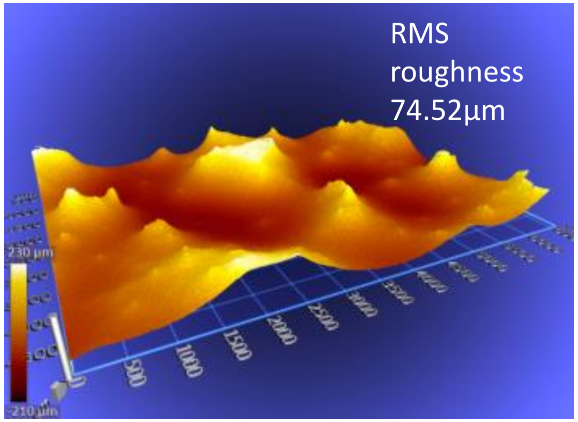
- Materials
  - Isotropic reflection
  - Specular to diffuse
  - Directional materials
- Modelling
  - Modelling directional materials
- Combat Identification: co-operative marking case
- Summary

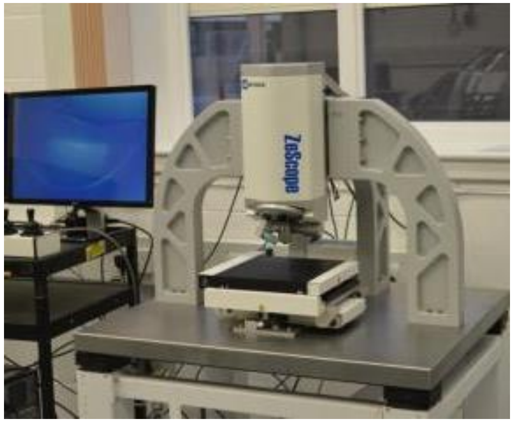
Specular to diffuse

Paints and metallised grit papers of different roughnesses were characterised on a ZeMetrics ZeScope white light interferometer to estimate their RMS roughnesses and correlation lengths.

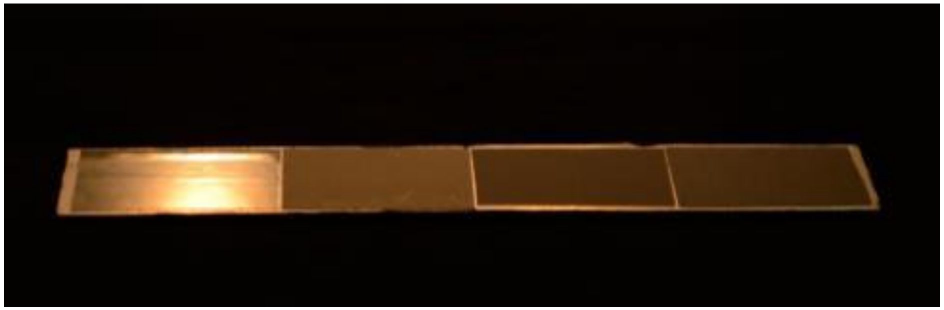
Hemispherical Directional Reflection (HDR) were characterised on a SOC-100: specular and diffuse components of reflection were calculated at a range of reflection angles.

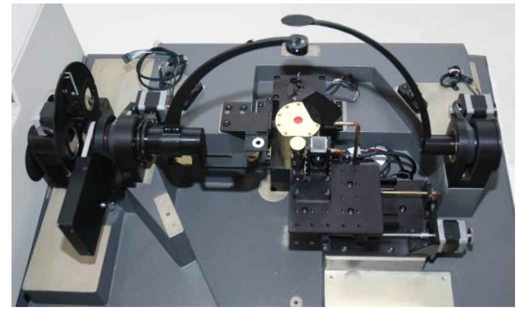


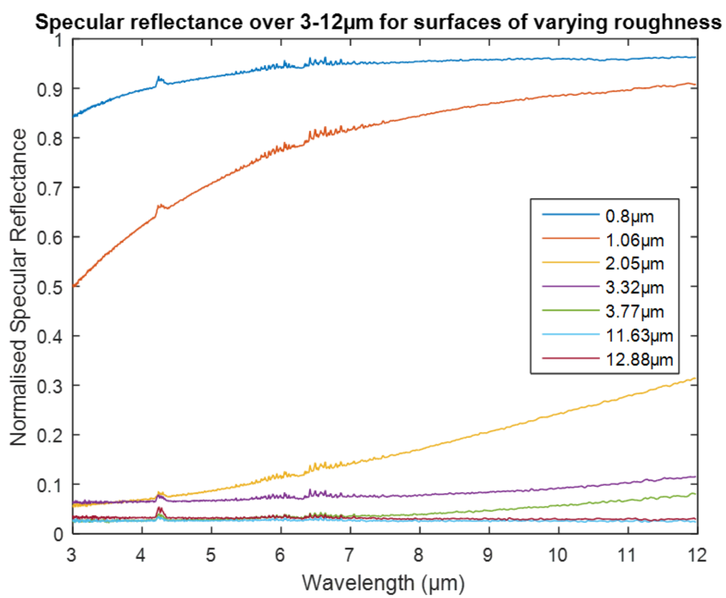


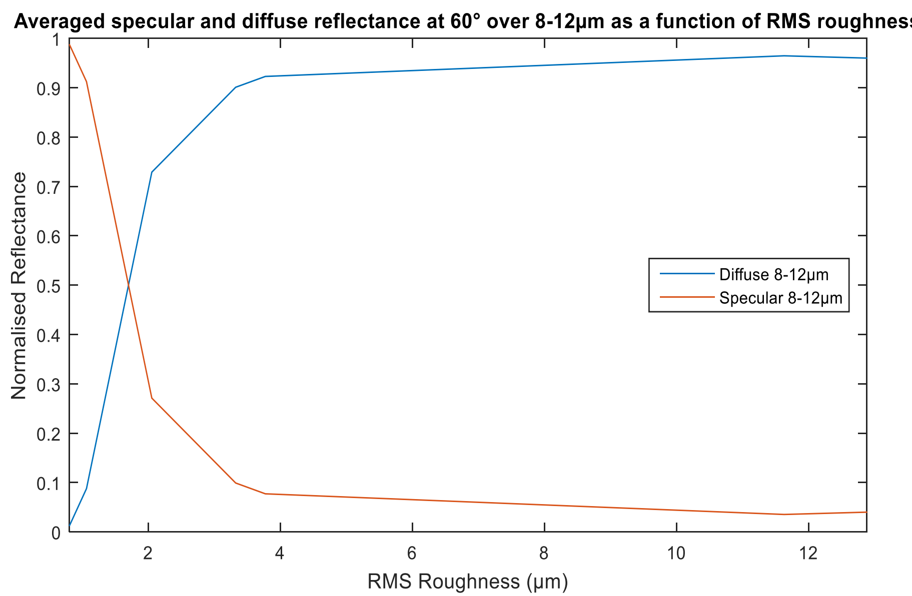


Metallised grit papers (TIR)

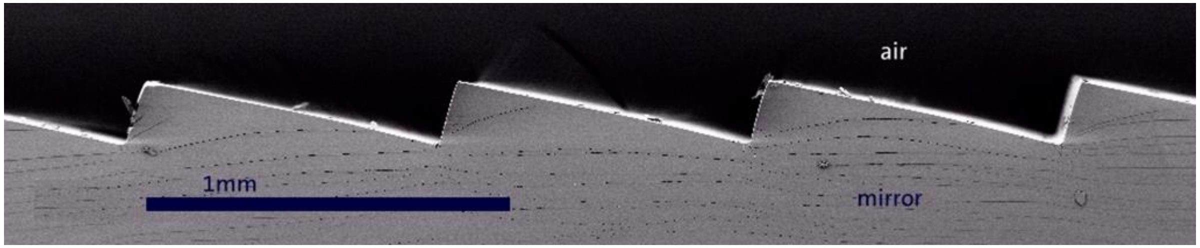


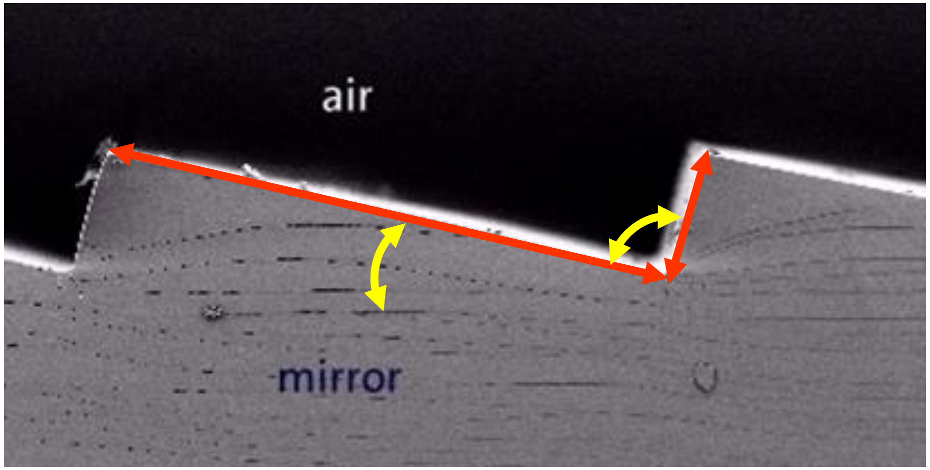


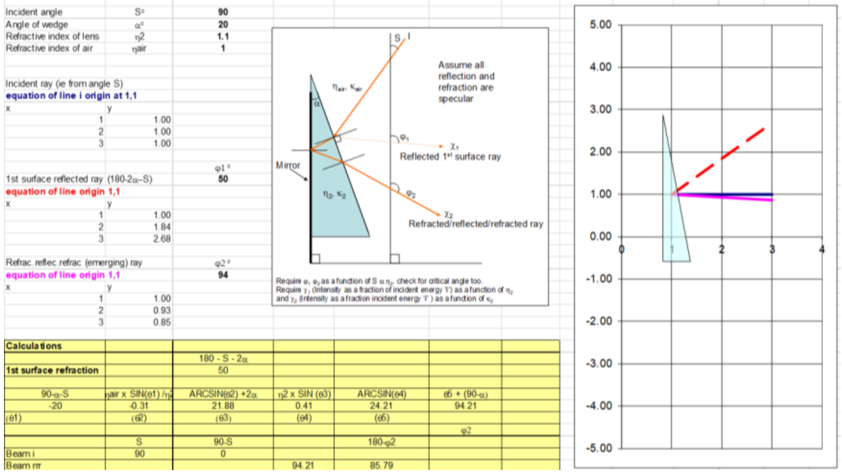




Directional materials – an example







Incident angle	S°	90
Angle of wedge	α°	20
Refractive index of lens	η2	1.1
Refractive index of air	ηair	1

Incident ray (ie from angle S)
equation of line i origin at 1,1

x	y
1	1.00
2	1.00
3	1.00

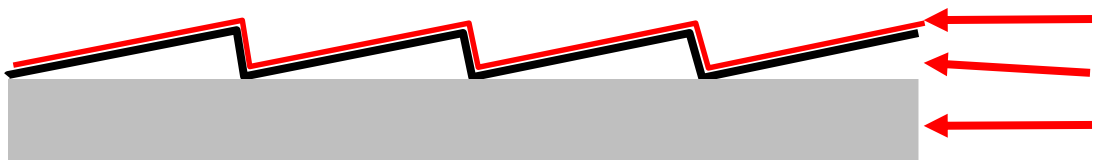
1st surface reflected ray (180-2α-S) φ1° **50**
equation of line origin 1,1

x	y
1	1.00
2	1.84
3	2.68

Refrac. reflec. refrac (emerging) ray φ2° **94**
equation of line origin 1,1

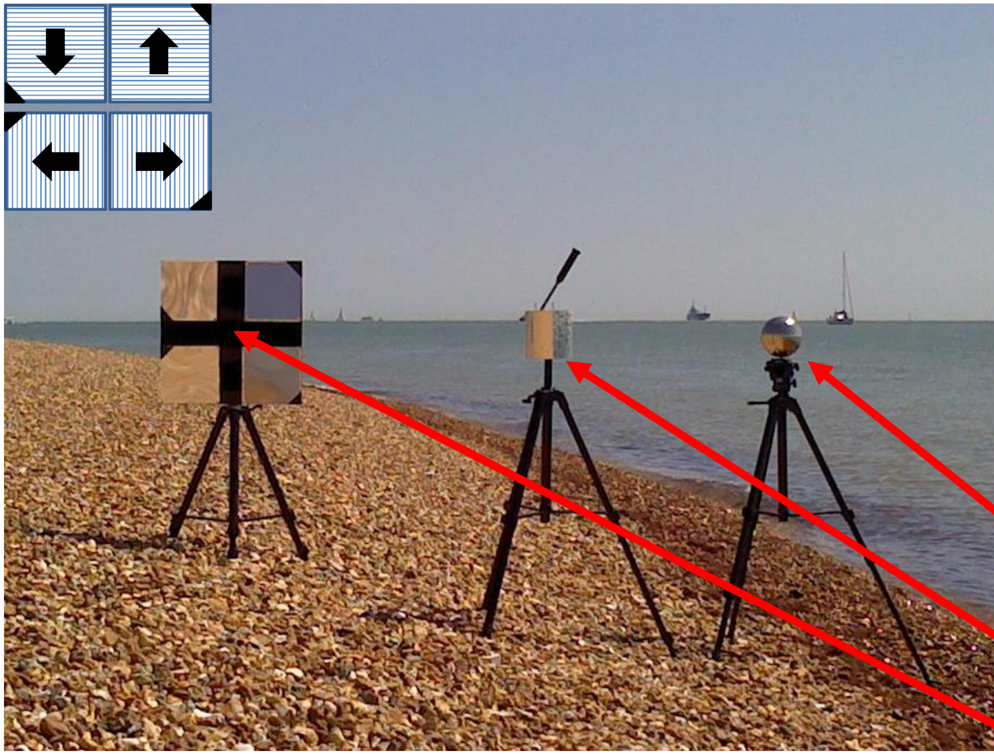
x	y
1	1.00
2	0.93
3	0.85

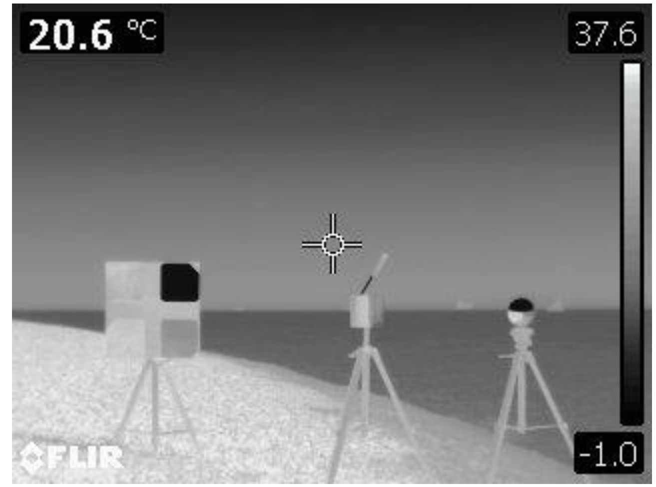
Calculations						
		180 - S - 2α				
1st surface refraction		50				
90-α-S	ηair x SIN(θ1) /η2	ARCSIN(θ2) +2α	η2 x SIN (θ3)	ARCSIN(θ4)	θ5 + (90-α)	
-20	-0.31	21.88	0.41	24.21	94.21	
(θ1)	(θ2)	(θ3)	(θ4)	(θ5)		
					φ2	
	S	90-S		180-φ2		
Beam i	90	0				
Beam rrr			94.21	85.79		



Thermal IR reflective surface
Nano-replicated microstructure
Polymer web

Directional materials – what they do





Three objects:

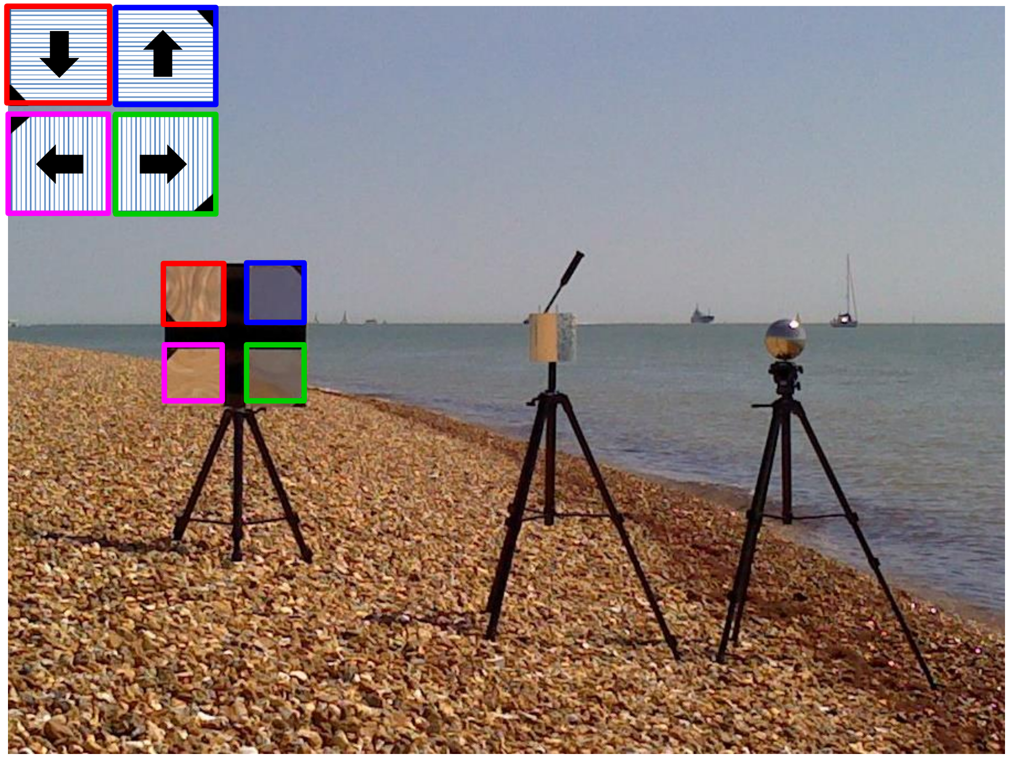
- specular mirror double curve (spherical Rh mirror)
- directional single curve (vertical axis of symmetry)
- directional flats

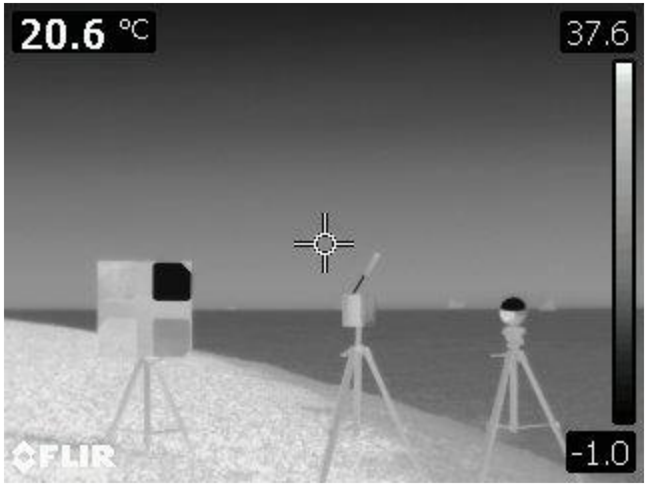
Directional flat quadrants, clockwise from top left:

Foreground	180°, beach shingle
Zenith	0°, clear sky
Right	90°, sea
Left	270°, beach shingle

Note that sun reflection is absent from the sphere in the LWIR image

Directional materials – what they do





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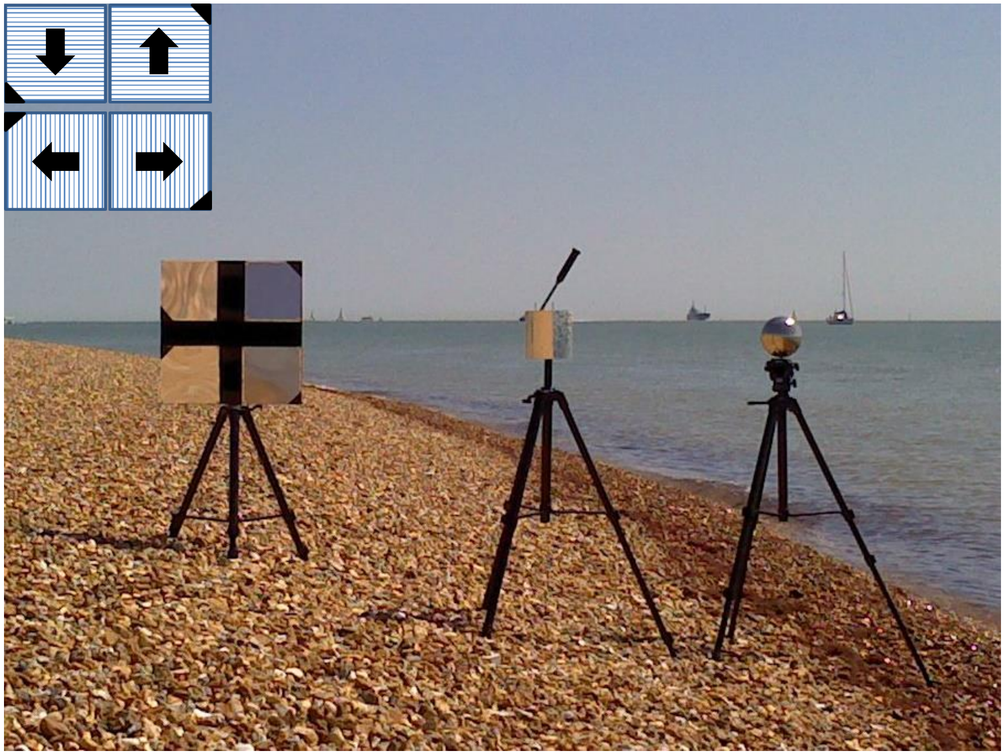

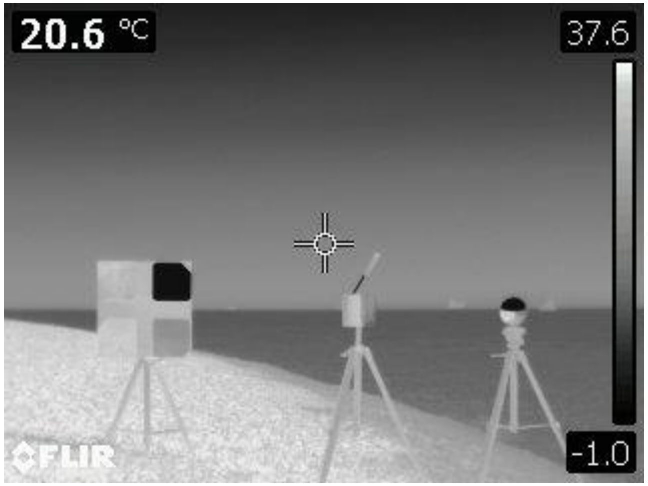

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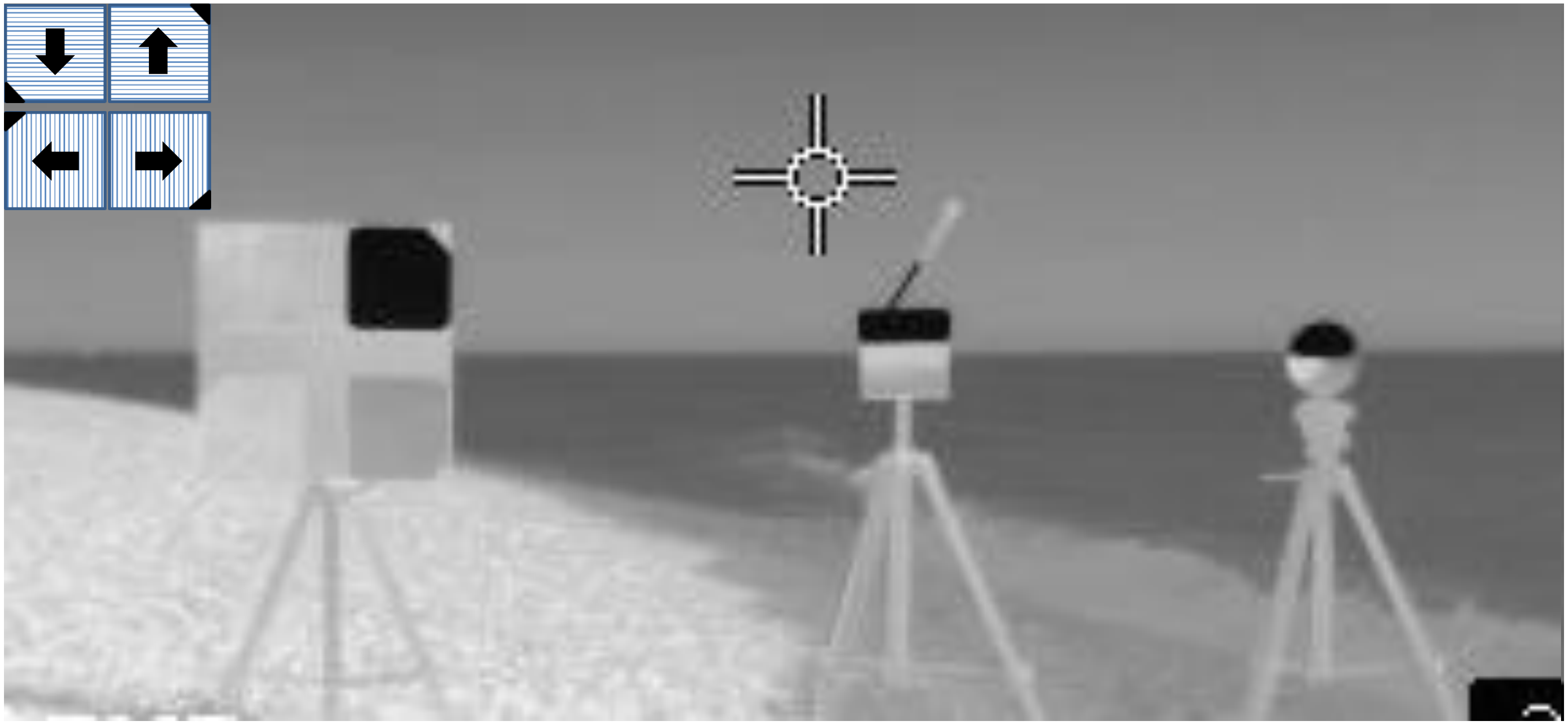

Directional flat quadrants, clockwise from top left:

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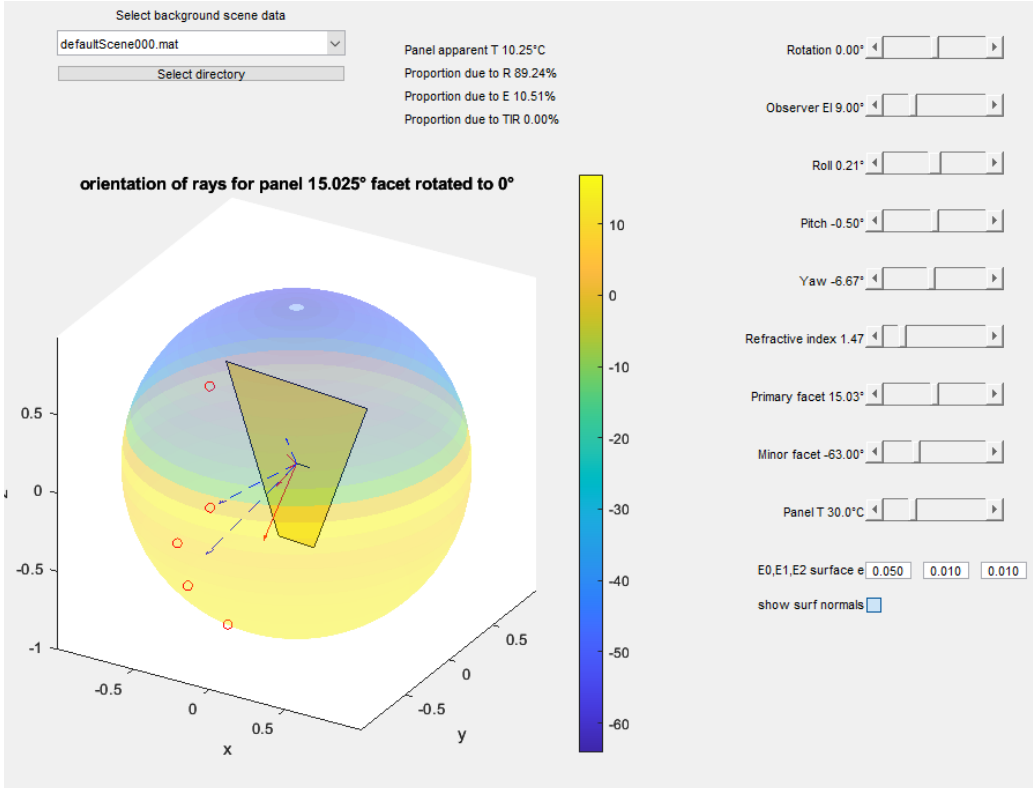
Modelling directional materials

Inputs:
- Micro-structure facet angles
- Facet emissivities
- Colour layer optical properties
- Surface temperature
- Environment temperatures
  - ➢ Statistical
  - ➢ Radiometric imagery (spherical mirror)
- Observer position
- Surface position
  - ➢ Pitch, roll, yaw

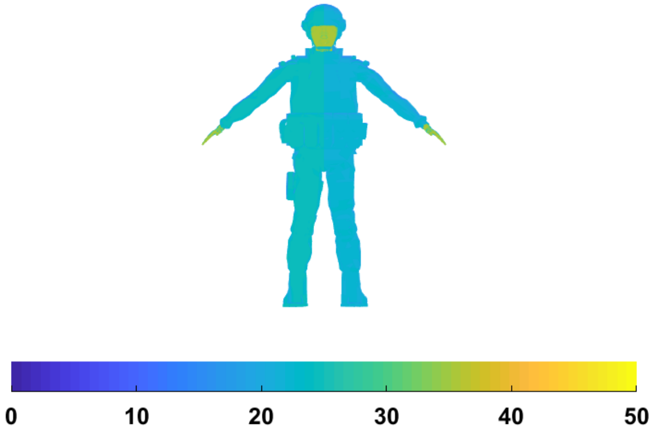
Output:
- Apparent temperature of surface



Surface model ⟷ Platform STL CAD → Platform fit

Modelling directional materials to control contrast radiant intensity (CRI)

Apparent temperature LWIR (8-12µm) predicted with:
Temperature of the outer garments 25°C, exposed skin 36°C
ambient air and horizon 10°C, sky zenith -20°C



Right-half of the figure treated with a Lambertian surface emissivity of 0.65.

CRI 209.4 W sr^{-1}

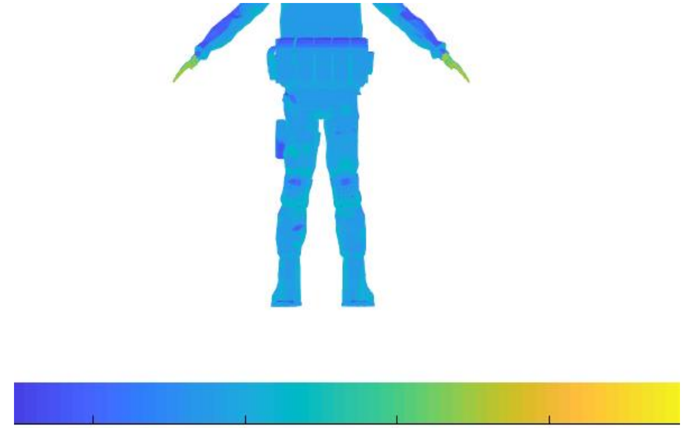
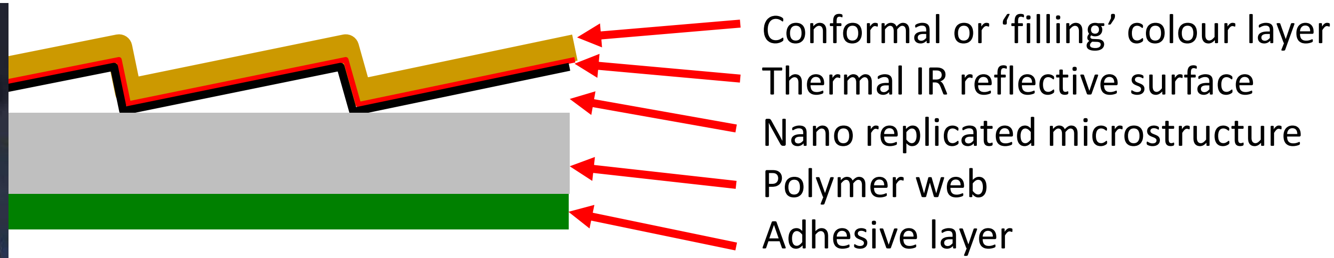


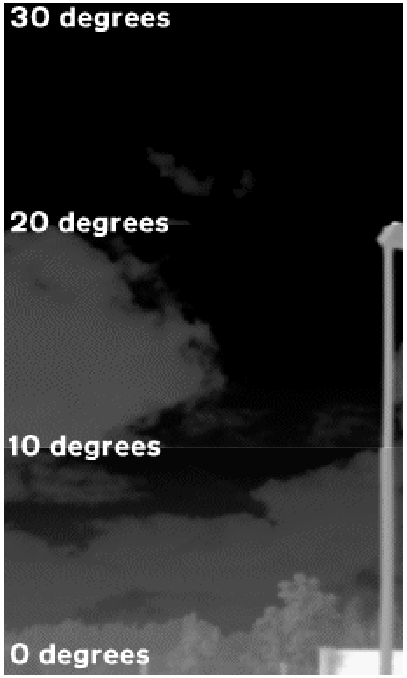
Figure treated with a ground-orientated coating with an emissivity of 0.21.

CRI 135.6 W sr^{-1}

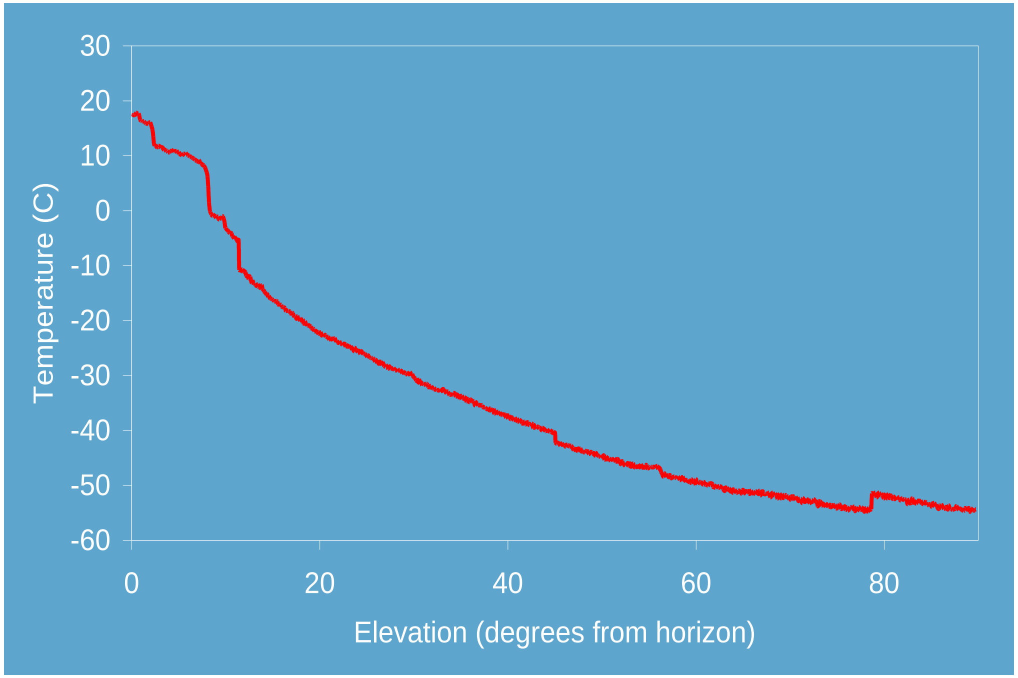
Combat Identification: co-operative marking case



Combat Identification co-operative marking case



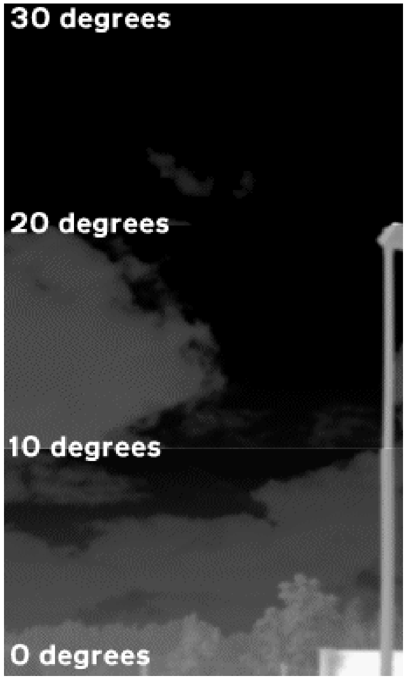
8-12 micron image of horizon to 30° elevation



Recorded apparent sky temperature with elevation

- At high elevation angles, the sky is very cold

Combat Identification co-operative marking case



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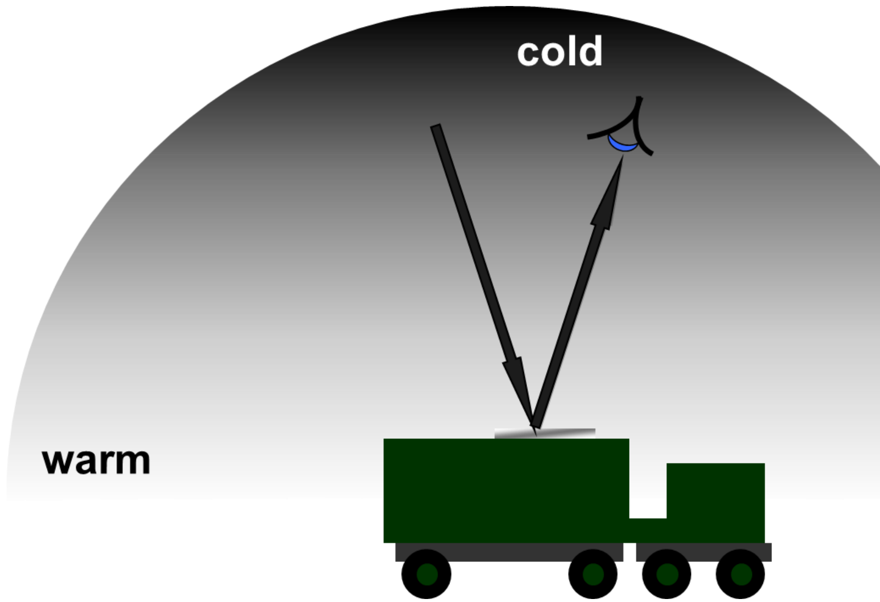
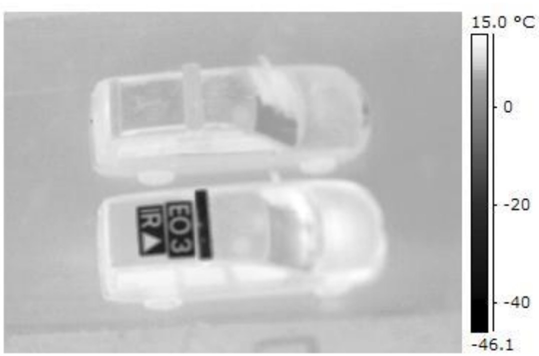
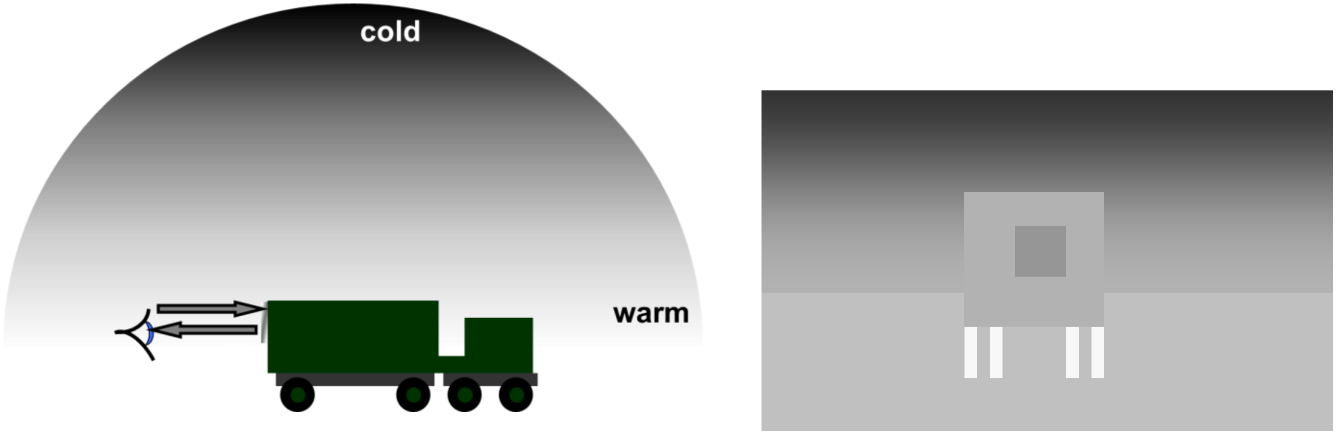


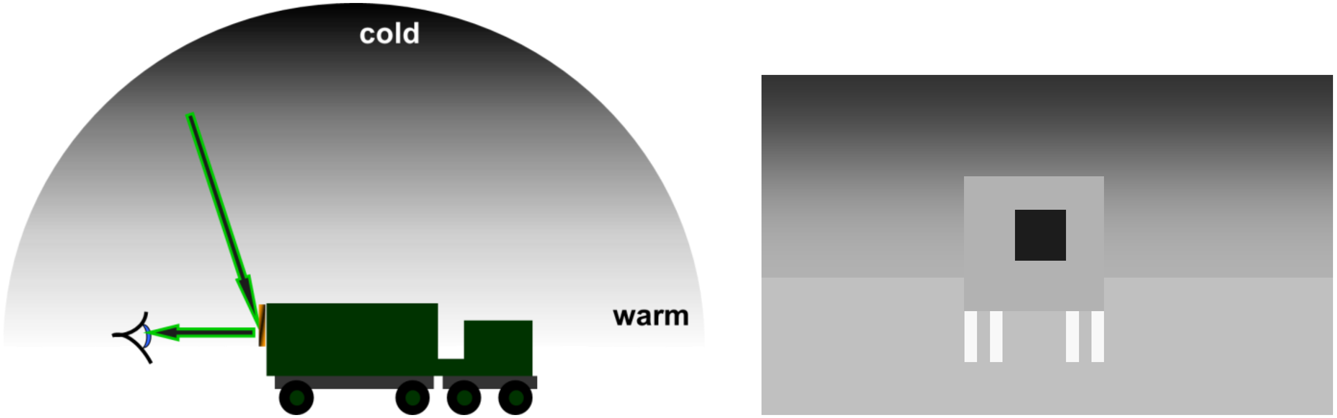
Mirage H is a visually coloured specular thermal infrared reflective mirror film. When placed on horizontal surfaces and viewed from above using thermal imaging equipment, it produces an apparently unnaturally cold mark.



Combat Identification co-operative marking case

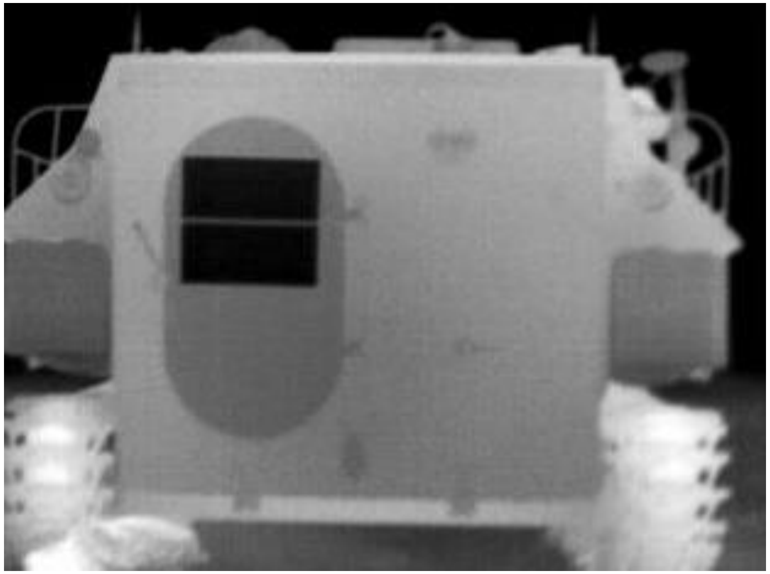


A plain mirror mounted on a vertical surface will reflect the warm horizon from most viewing directions: consequently, little thermal contrast with the vehicle body.



A directional mirror designed to reflect high elevation cold sky: this gives high thermal contrast with the vehicle body.

Combat Identification co-operative marking case



Summary

- **I hope that I have shown you:**
  - The thermal IR threat posed by peer & near-peer adversaries is current & evolving
  - CCD is a significant part of Integrated Survivability, the thermal IR increasingly so
  - FDEOS kits help troops to understand & optimise counter surveillance control measures
  - Controlling thermal IR emissivity can reduce susceptibility to detection by thermal IR sensors
  - Uncontrolled reflections can impair thermal IR camouflage effectiveness
  - Directional materials can be used to minimise this impairment
  - Application of thermal IR directional materials as a cooperative combat marking material has been discussed
- **Finally: there are many variations of directional materials and platform fits that can be considered. It is up to the intelligent camouflage designer to optimise the outcome.**