CSIR

Defence, Peace, Safety and Security

Aircraft vulnerability analysis by modelling and simulation

Nelis Willers, Riana Willers & Alta de Waal

Presented by: Kevin Gopaul

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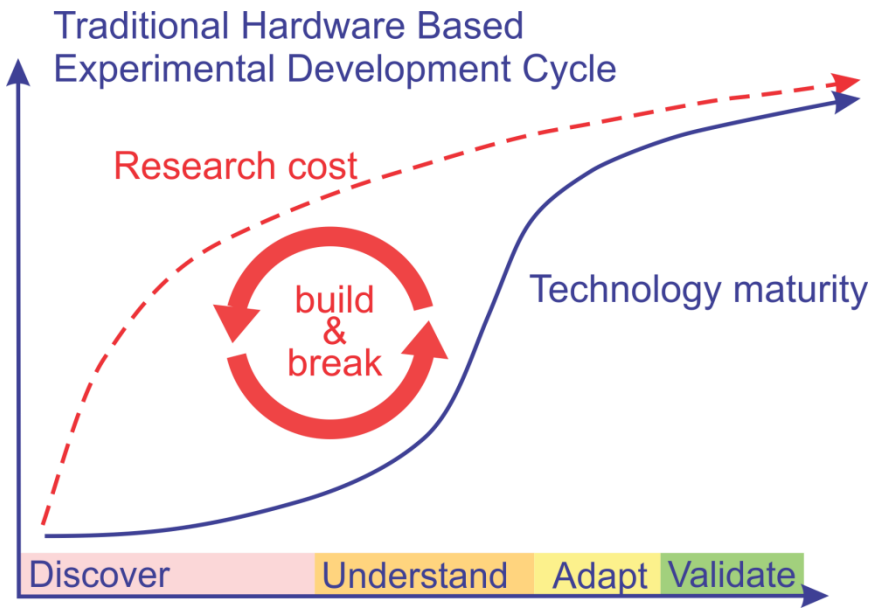
“Science advances one funeral at a time”

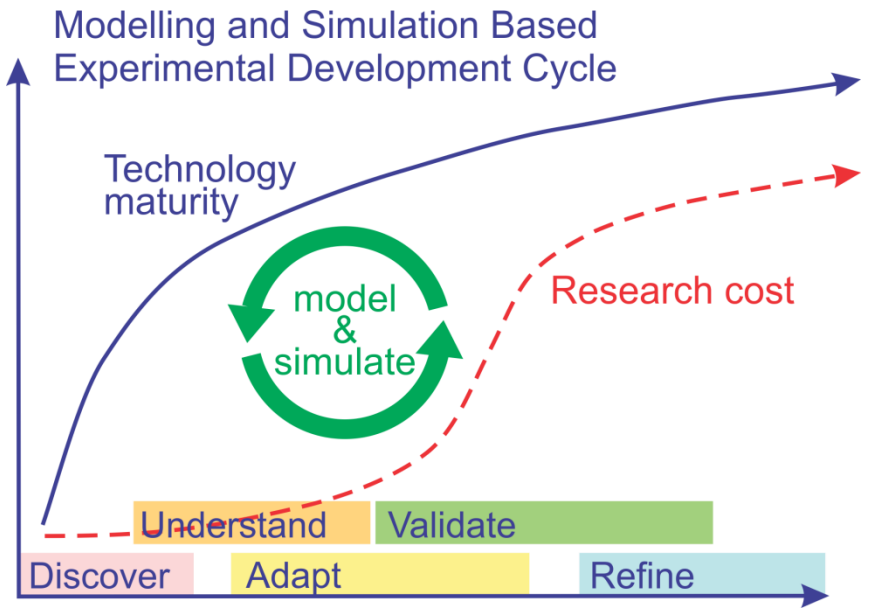
Max Planck (1858 – 1947)

Background

- Introducing various concepts
- The information in this presentation
  - you have seen before, and
  - is publicly available
- You will, however,
  - see it in a different way, and
  - hopefully acquire one or two new insights
- Security
  - Models used are desensitised (some available online)
  - Illustrate the thesis of this paper
- **Significant modelling and computational effort** – only some of the results are reported here

Introduction





- "Build and break" hardware.
- Labour, time & cost intensive.
- Workflow highly linear.

- Design by software changes.
- Experiment at lower cost & risk.
- Workflow in parallel paths.

Graphics adapted from Airbus Industries pamphlet

Introduction

- The software/simulation must be:
  - **representative**,
  - **accurate**, and
  - **validated**

- We **do not** want:

Top 20 Replies by Programmers when their programs don't work...

20. That's weird...
19. It's never done that before.
18. It worked yesterday.
17. How is that possible?
16. It must be a hardware problem.
15. What did you type in wrong to get it to crash?
14. There has to be something funky in your data.
13. I haven't touched that module in weeks!
12. You must have the wrong version.
11. It's just some unlucky coincidence.
10. I can't test everything!
9. THIS can't be the source of THAT.
8. It works, but it hasn't been tested.
7. Somebody must have changed my code.
6. Did you check for a virus on your system?
5. Even though it doesn't work, how does it feel?
4. You can't use that version on your system.
3. Why do you want to do it that way?
2. Where were you when the program blew up?
1. It works on my machine.

Overview

- **Optical signatures**
- 3D background radiance
- Hemispherical irradiance
- Aircraft model and signature
- Missile model

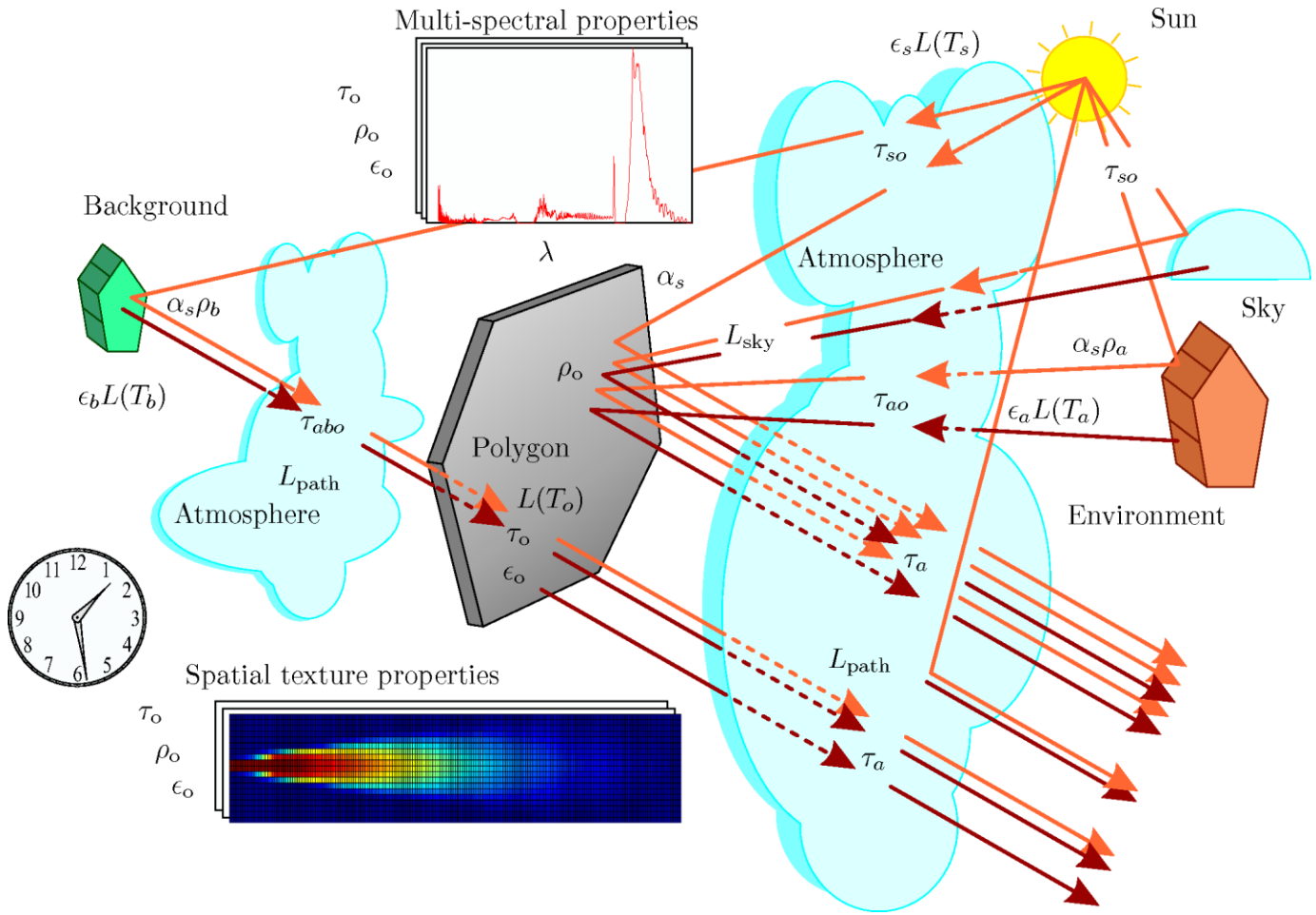
- Miss distance prediction
- Miss distance data fusion

Optical Signatures

- An **infrared signature** depends on many factors:
  - Shape and size of the object
  - Temperature and emissivity
  - Surface reflection of external sources (earth, sun, sky)
  - Transmittance through the object
  - Background against which (and atmosphere through which) it is viewed

- Apparent signature changes with changes in:
  - Weather and atmospheric conditions
  - Time of day
  - External and internal heat sources

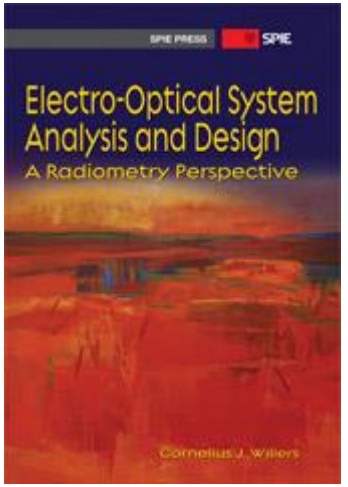
Optical Signatures – Signature Rendering Model



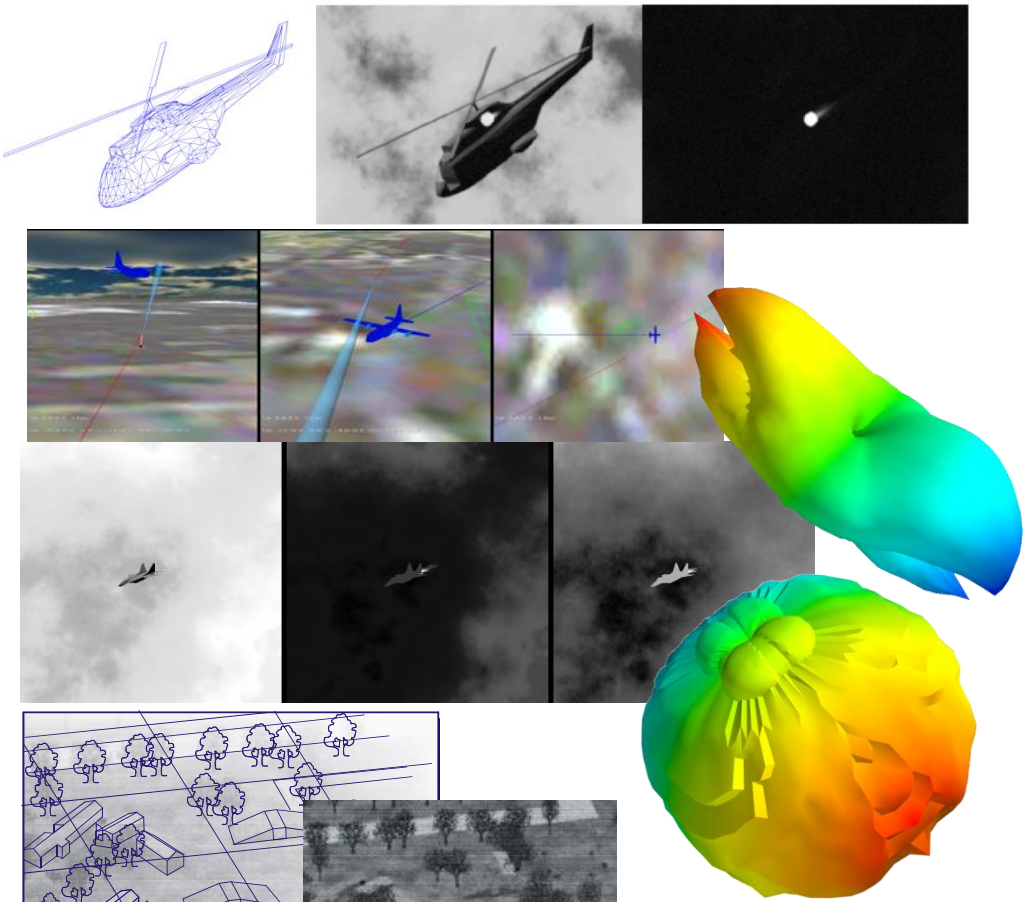
Optical Signatures

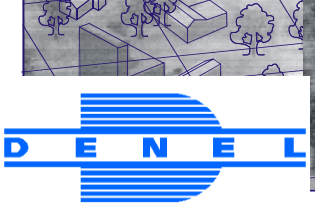
$$
\begin{aligned}
L_{\mathcal{S}} = {} & \overbrace{\Delta_\epsilon \int_0^\infty \epsilon_{o\lambda}(\theta_v) L_\lambda(T_o) \tau_{a\lambda} \mathcal{S}_\lambda d\lambda}^{\text{thermally emitted } L_{\text{self}}} + \overbrace{\int_0^\infty \tau_{o\lambda} \epsilon_{b\lambda} L_\lambda(T_b) \tau_{abo\lambda} \tau_{a\lambda} \mathcal{S}_\lambda d\lambda}^{\text{transmitted background } L_{\text{trn back}}} \\
& + \overbrace{\Delta_\rho \int_0^\infty \int_{\text{env}} \rho_{o\lambda} \epsilon_{a\lambda} L_\lambda(T_a) \tau_{ao\lambda} \tau_{a\lambda} \mathcal{S}_\lambda d\Omega d\lambda}^{\text{diffuse reflected ambient background } L_{\text{ref amb}}} + \overbrace{\Delta_\rho \cos\theta_a \int_0^\infty \int_{\text{sky}} \rho_{o\lambda} L_{\text{sky}\lambda} \tau_{a\lambda} \mathcal{S}_\lambda d\Omega d\lambda}^{\text{diffuse reflected sky } L_{\text{ref sky}}} \\
& + \overbrace{\Delta_\rho \psi \cos\theta_s \int_0^\infty f_r(\theta_i, \theta_s, \varphi_i, \varphi_s) \epsilon_{s\lambda} L_\lambda(T_s) \tau_{so\lambda} \tau_{a\lambda} \mathcal{S}_\lambda d\lambda}^{\text{reflected sun } L_{\text{ref sun}}} + \overbrace{\int_0^\infty L_{\text{path}\lambda} \mathcal{S}_\lambda d\lambda}^{\text{atmospheric path radiance } L_{\text{path}}}
\end{aligned}
$$

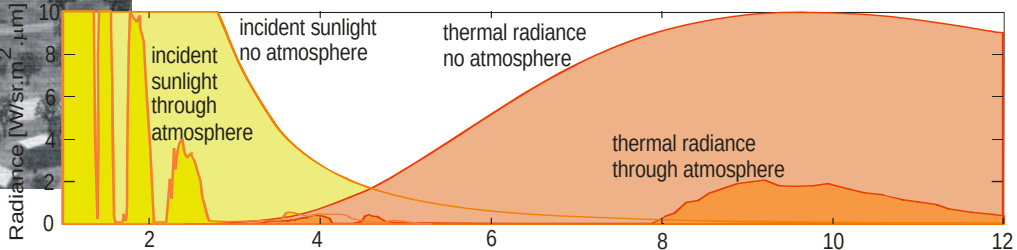
(Willers 2013)



Optical Signatures – Optronic System Simulator (OSSIM)







- Multi-colour 0.4-14 µm images of complex user-defined scenes
- End-to-end physically accurate: atmosphere, sun and infrared self radiance: create ‘real’ images
- Fully 3D
- 6 DOF movement.
- Objects visible to all other, has body
- Modtran interface, full capability
- Full-system modelling capability
- Simulate complex scenarios

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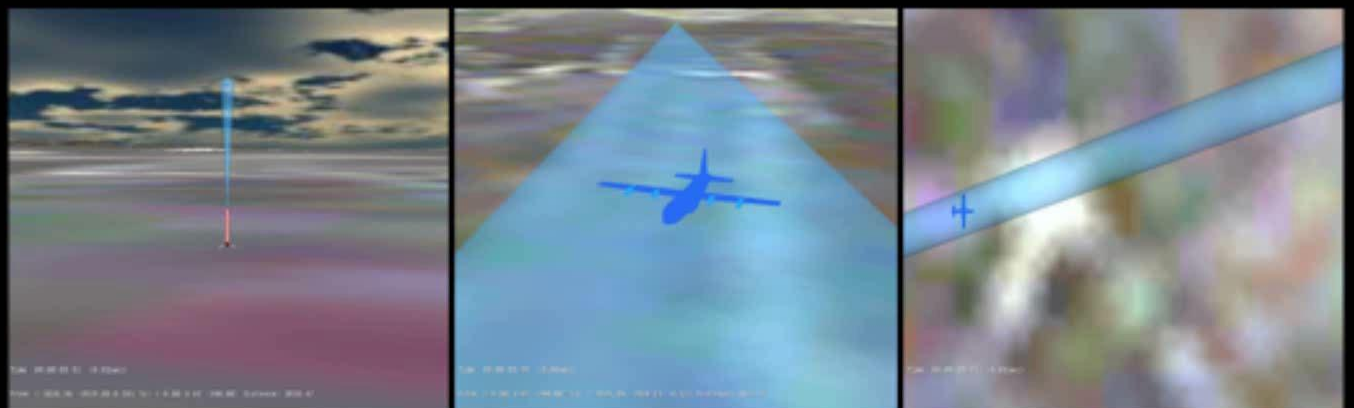
Optical Signatures – Optronic System Simulator (OSSIM)

- **Aircraft Vulnerability Simulation**



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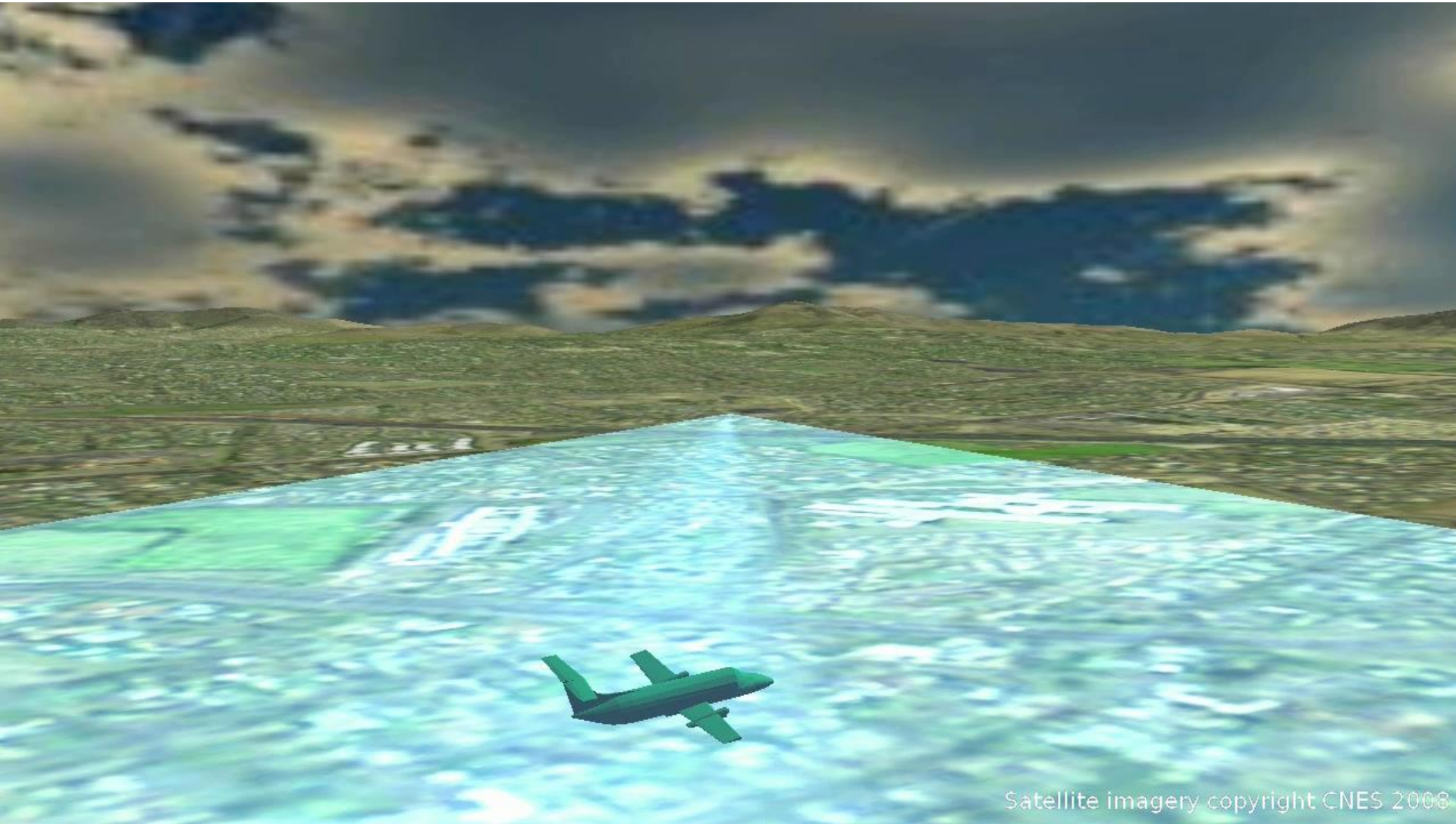

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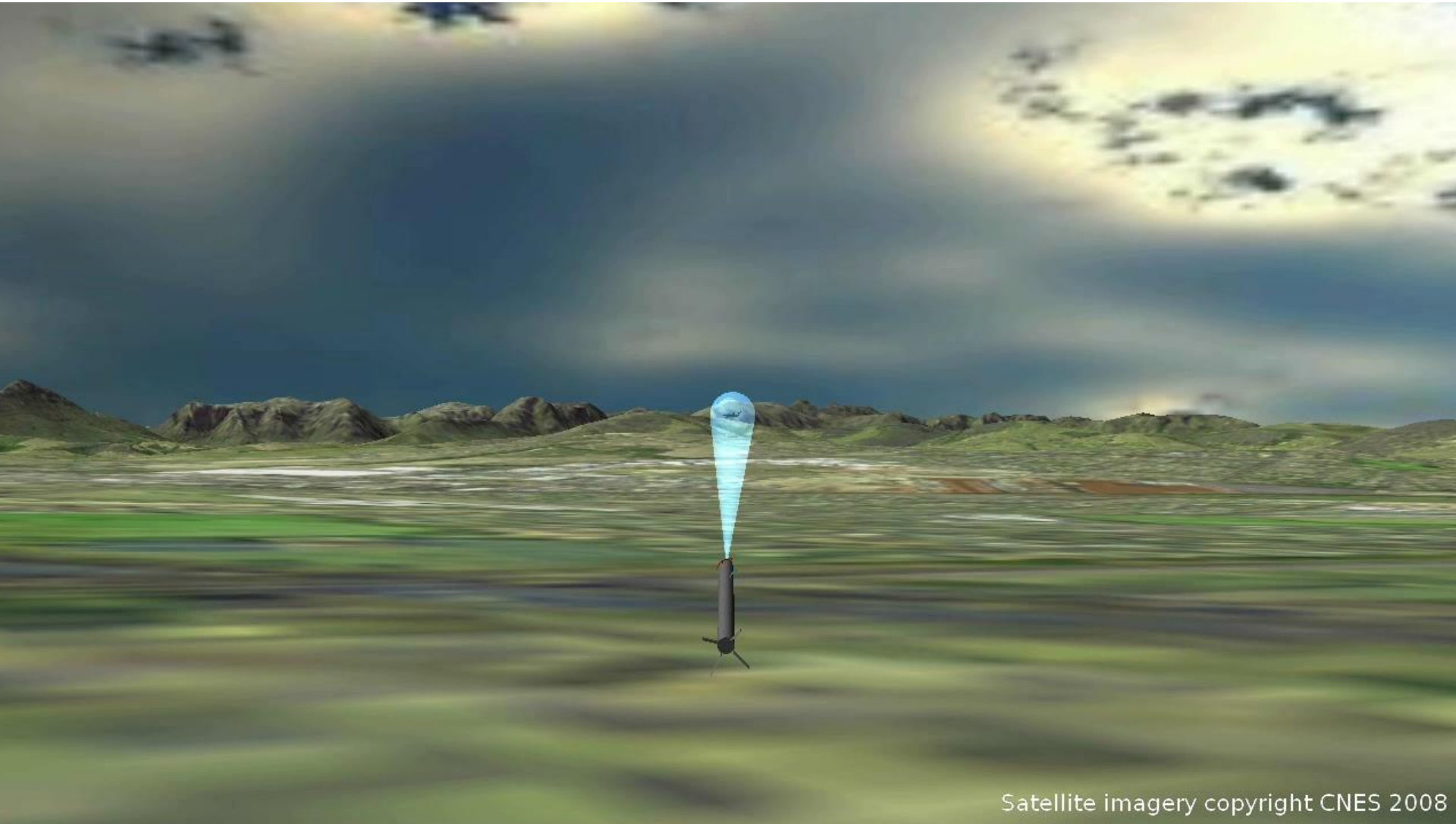

Overview

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- **3D background radiance**
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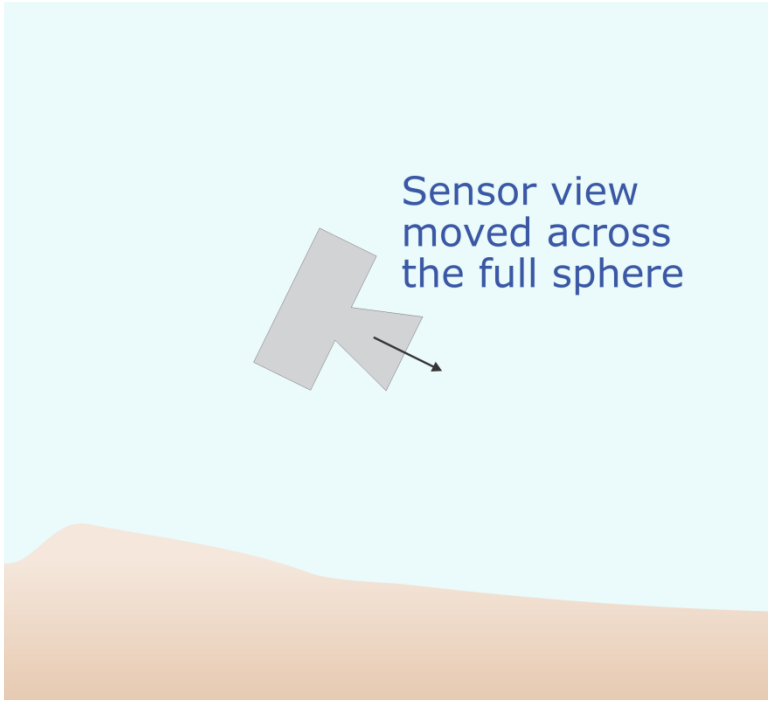
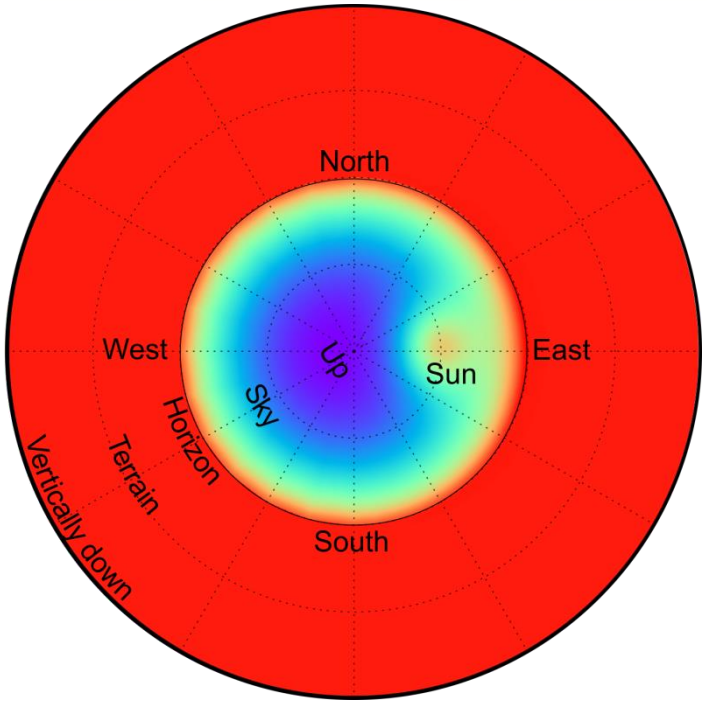
- Miss distance data fusion

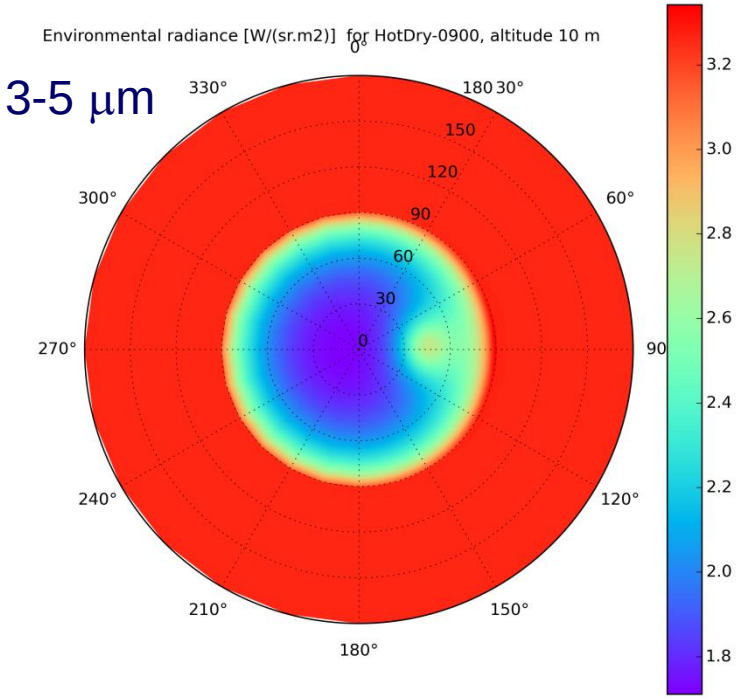
Background Radiance (Skydome)

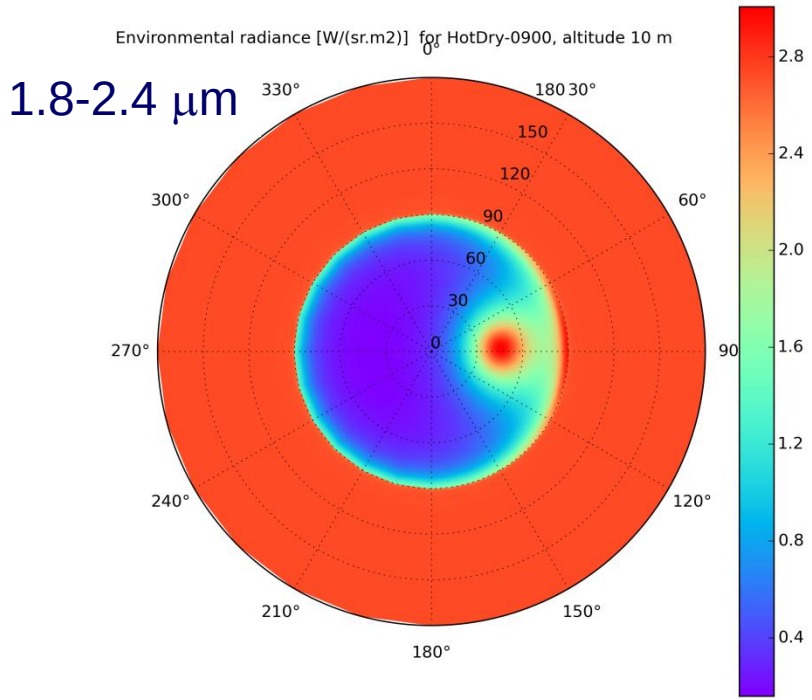




- Use Modtran to calculate **radiance** for all views over sphere: sky (up), horizon and terrain (down)
- Sensor image painted with skydome first and then paint the target and scene radiance in front of skydome
- **Missile sees this background too**

Background Radiance (Skydome)





- 09:00 in `Desert Extinction' aerosol model, 10 km visibility, 10 m alt

The target intensity is seen as a contrast against this radiance.

Overview

- Optical signatures
- 3D background radiance
- **Hemispherical irradiance**
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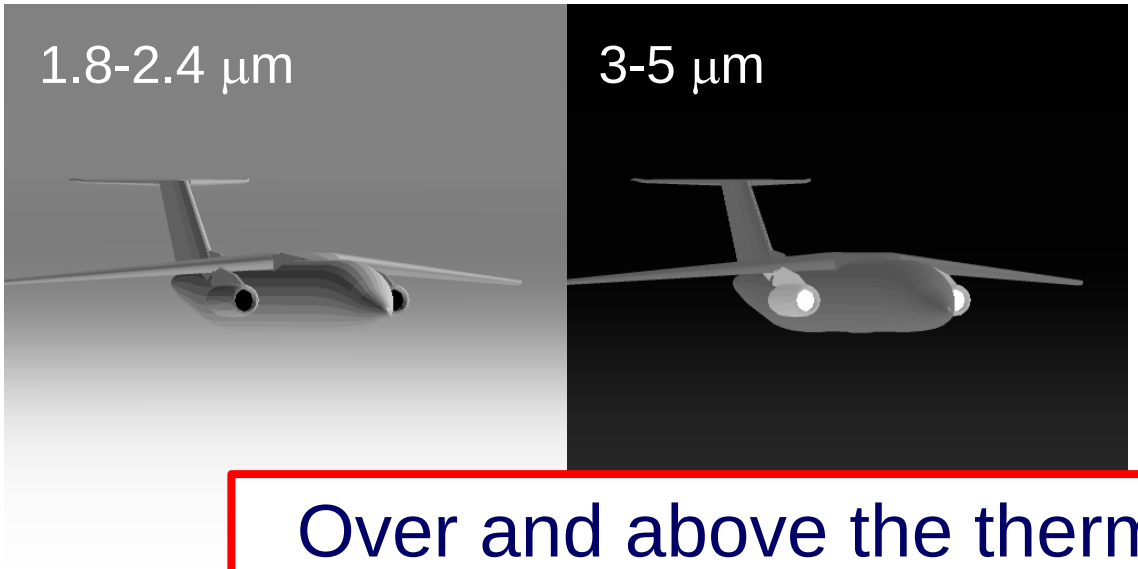
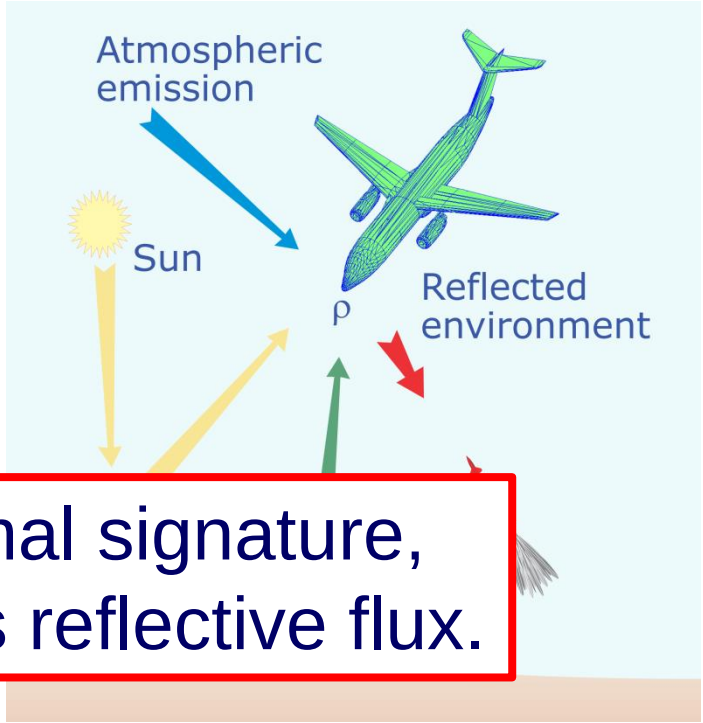
Hemispherical Irradiance – Earth Shine and Sky Shine





Over and above the thermal signature, the target also radiates this reflective flux.

- Earth shine and sky shine irradiate the target
- Significant effect if there is no visible hot metal or open plume
- Could provide positive contrast against dark sky in SWIR
- Especially important for near-zero contrast scenarios

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- **Aircraft model and signature**
- Missile model

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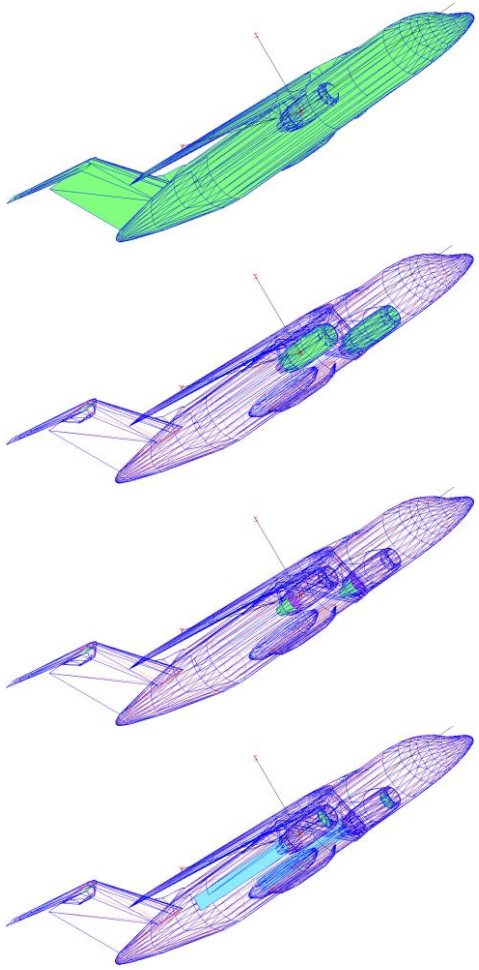
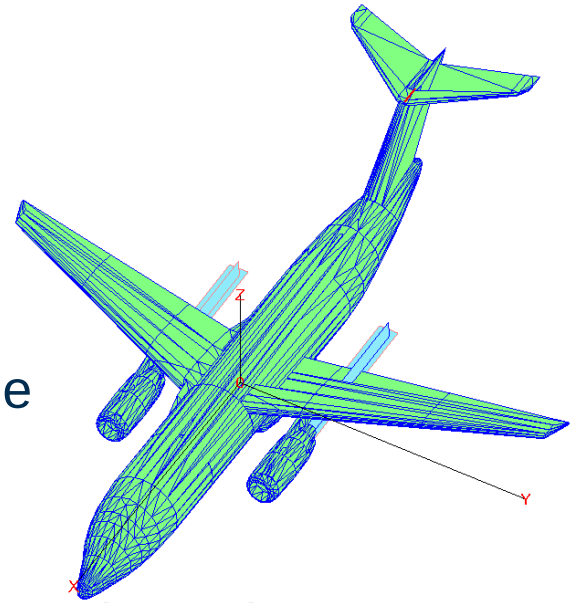
Aircraft Model and Signature



- Antonov 148
- 30 m wingspan
- 80 seats (15 tons)
- Twin turbofan
- Wireframe purchased online



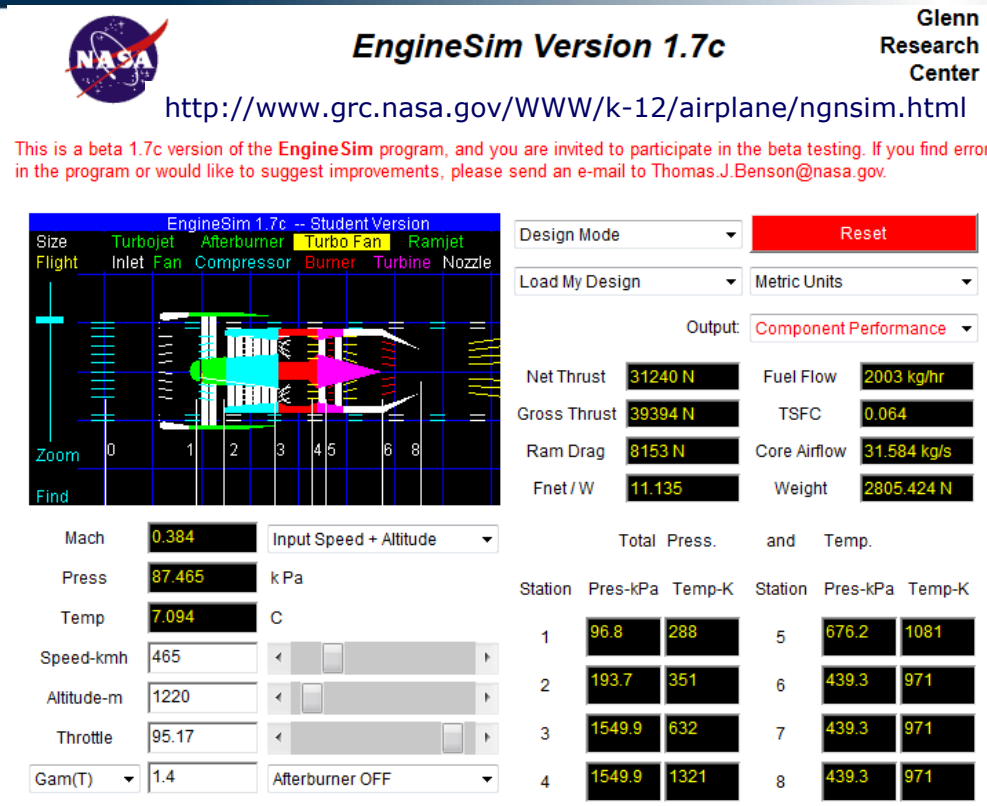
<u>Geometric model</u>

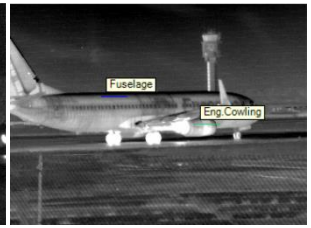
- 2871 polygons
- 10 poly classes
- Plume

<u>Radiometric model</u>

- Emissivity
- Reflectance
- Temperature

Aircraft Model and Signature – Engine EGT

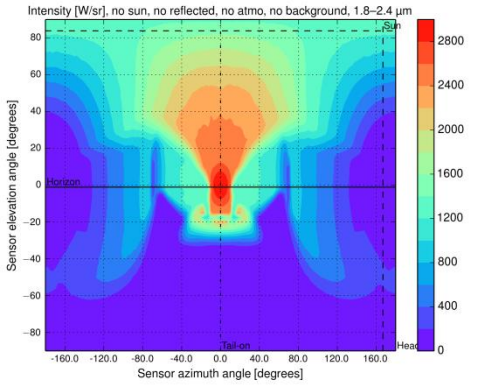




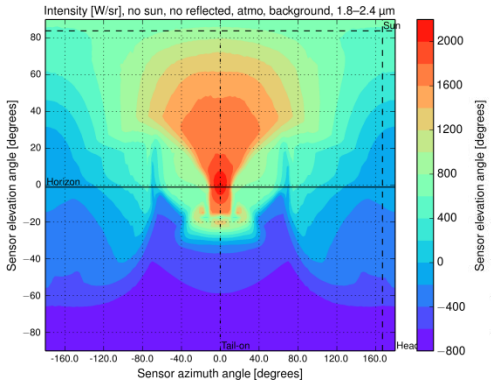
Throttle setting	Altitude [m]						
	0.0	1220.0	3000.0	5000.0	8000.0	12000.0	19800.0
100.0	980.0	988.6	1001.9	1016.2	1038.0	1060.8	1060.8
98.0	953.4	972.4	976.2	990.5	1012.4	1035.2	1035.2
95.0	912.5	923.0	934.4	949.6	971.5	993.3	993.3
82.0	731.9	741.4	754.7	770.0	792.8	815.6	815.6
73.0	616.9	616.9	630.2	645.4	669.2	692.0	692.0
70.0	565.6	575.1	588.4	603.6	627.4	651.1	651.1
68.0	537.1	549.4	560.8	576.0	599.8	622.6	622.6
65.0	494.3	499.0	518.1	534.2	557.0	580.8	580.8
%	K	K	K	K	K	K	K

- Turbofan exhaust gas temperature
  - Ground reference measurements
  - NASA model for missing data
  - Cross validation on measure points

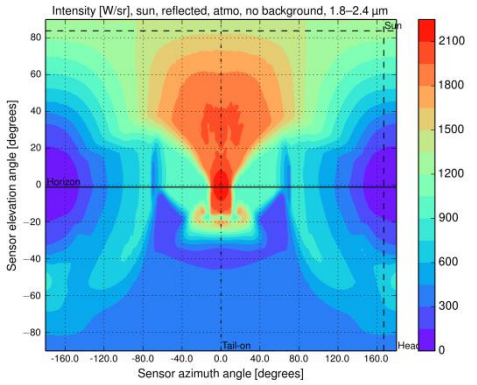
Aircraft Model and Signature – 1.8 – 2.4 µm



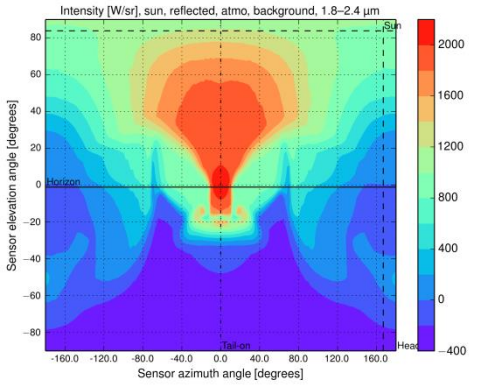
Absolute intensity:
thermal only
0 – 2800 W/sr



Contrast intensity:
thermal only
-800 – 2100 W/sr



Absolute intensity:
comprehensive
0 – 2100 W/sr



Contrast intensity:
comprehensive
-400 – 2100 W/sr

- 3D signature complex function of view
- Engine and fuselage geometry has significant effect
- All radiometry terms required to be **included**
- All radiometry terms required to be **accurate**

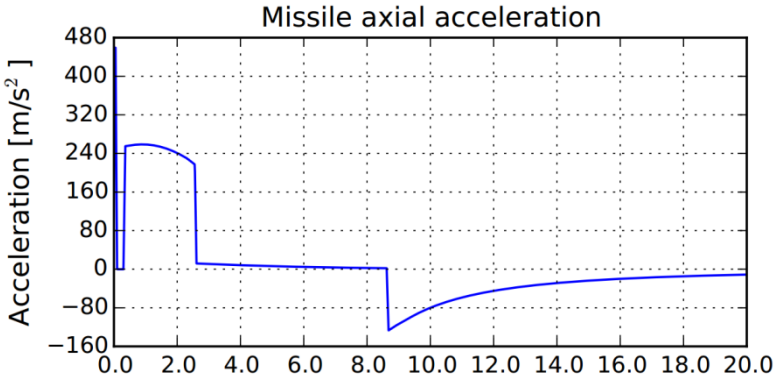
Overview

- Optical signatures
- 3D background radiance
- Hemispherical irradiance
- Aircraft model and signature
- **Missile model**

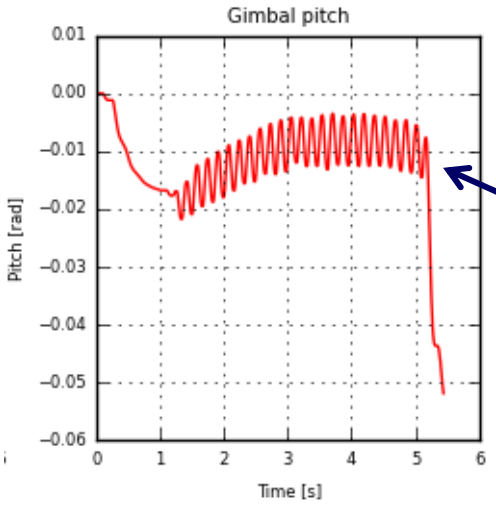
- Miss distance prediction
- Miss distance data fusion

Missile Model

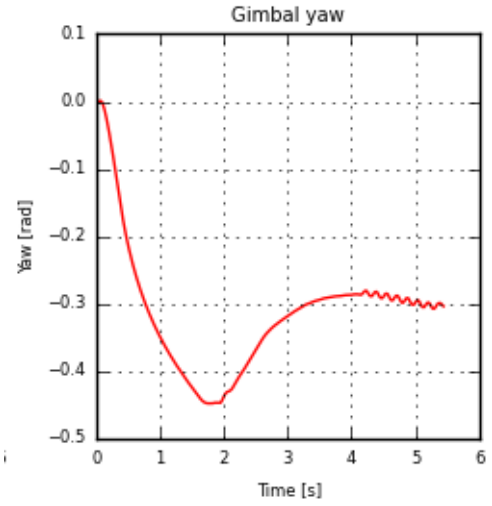
- Two-axis gimballed platform
- Maximum look angle of ±40 deg
- Tracking rate is limited to 20 deg/s
- Field of view 1.5 degrees
- NEE = 2.0×10^{-7} W/m^2
- $E_{threshold} = 1 \times 10^{-6}$ W/m^2 (SNR=5)
- 1.8–2.4 µm spectral response
- Max airframe lateral acceleration 6g



Gimbal info: Birchenall, Richardson, Butters, and Walmsley, Infrared Physics & Technology 53, 372–380 (2010).
Missile and sensitivity from first principles calculations



Limit cycle



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Missile Model – Missile Centroid Tracker

Contrast irradiance (offset removal)

$$E(i,j)_c = \|E(i,j) - \langle E \rangle\|$$

Select pixels exceeding a fixed threshold

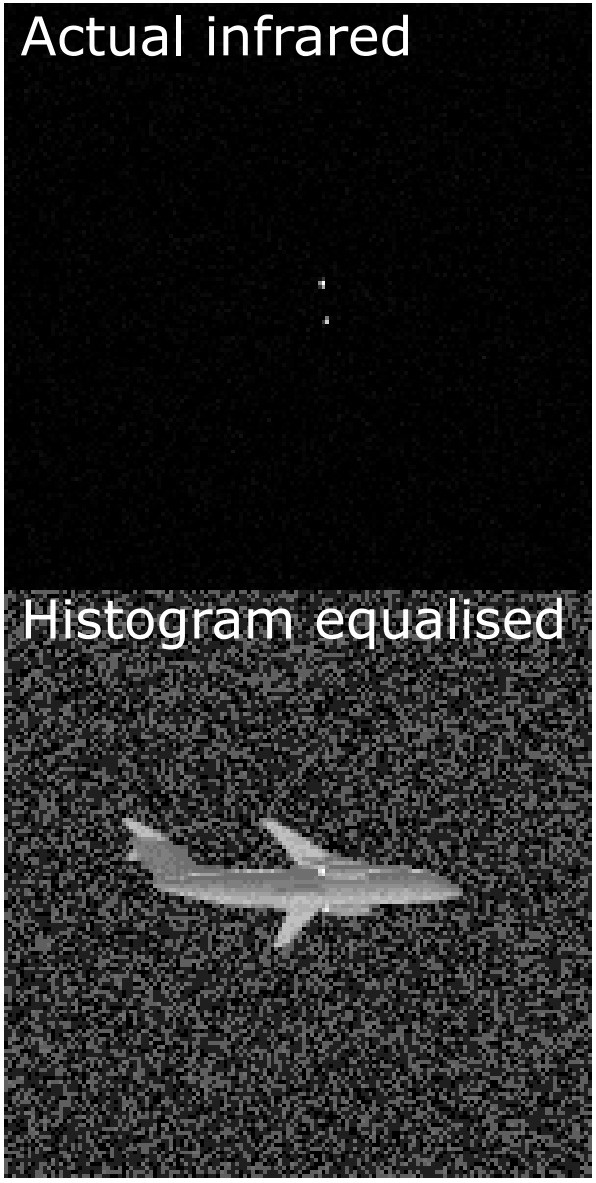
$$E(i,j)_c > E_\theta$$

Centroid of selected pixels

$$(\bar{i}_t, \bar{j}_t) = \left(\frac{\sum_i \sum_j i E(i,j)_c}{\sum_i \sum_j E(i,j)_c}, \frac{\sum_i \sum_j j E(i,j)_c}{\sum_i \sum_j E(i,j)_c} \right)$$

Target detected and tracked if

$$\sum_i \sum_j E(i,j)_c > 0$$



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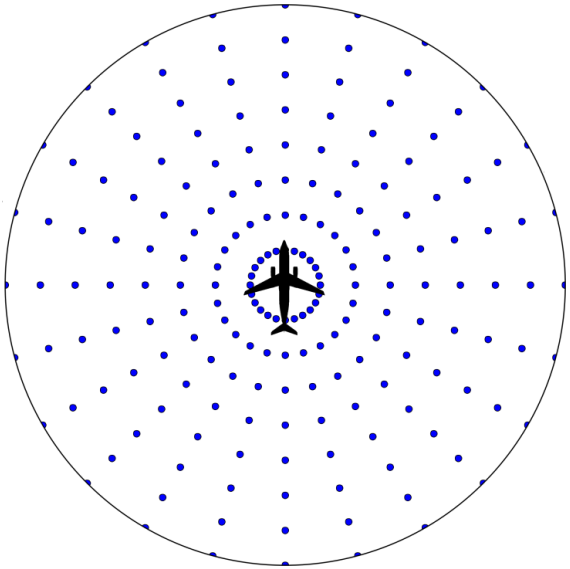
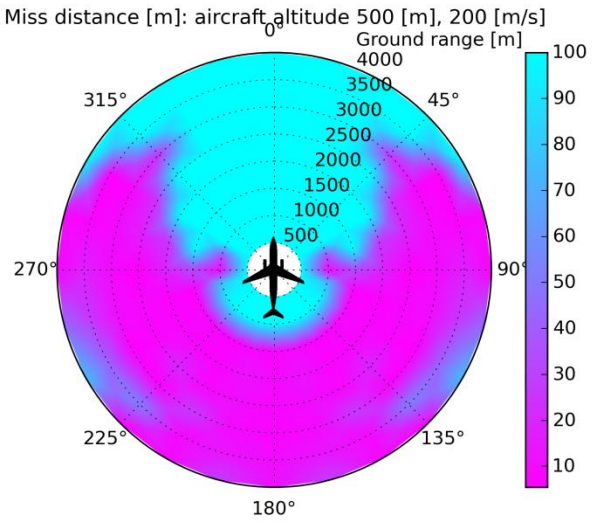
- **Miss distance prediction**
- Miss distance data fusion

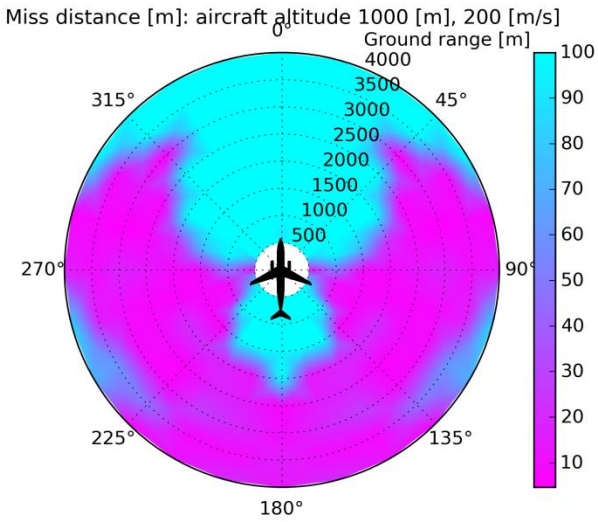
Miss Distance Prediction

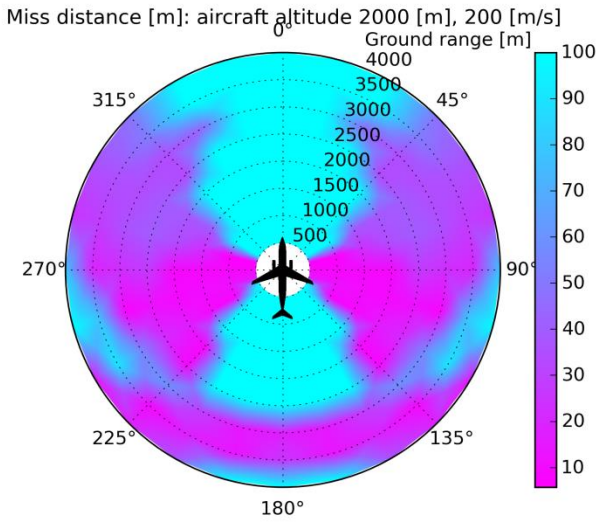
- In simulation, launch missiles at:
  - 15 degree intervals
  - 500 m intervals
- Find minimum distance between aircraft and missile
- Termination condition:
  - Miss distance increases
  - Target leaves sensor FOV
  - Target signal below threshold



Miss Distance Prediction







- Example
  - Constant altitude (500, 1000, 2000) m
  - Zero pitch
  - 90% throttle setting
- Colour → minimum distance between target and missile
- Countermeasure – single MTV flare

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- **Miss distance data fusion**

Miss Distance Data Fusion – Bayesian Networks

- Bayesian Network (BN)
  - Graphical models for reasoning under **complexity** and **uncertainty**
  - Marriage between **probability** theory and **graph** theory
  - Consists of **nodes** and **edges**
  - **Nodes** depict **variables**
  - **Edges** depict **causal links** between nodes

  - Different types of knowledge and data can be fused into one network
  - Handles missing data
  - **Powerful inference engine**

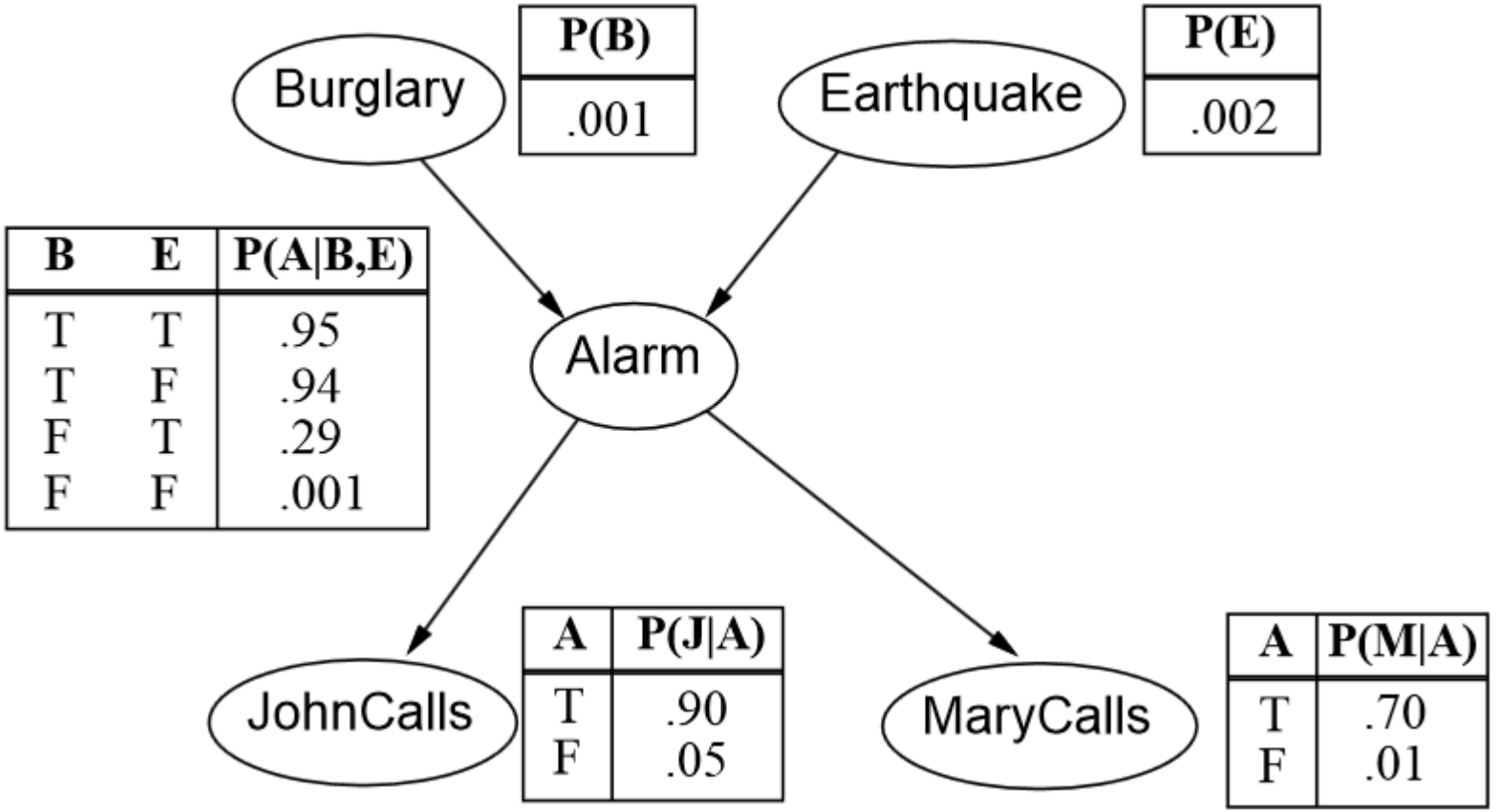
Miss Distance Data Fusion – Bayesian Networks

I'm at work, neighbor John calls to say my alarm is ringing, but neighbor Mary doesn't call. Sometimes it's set off by minor earthquakes. Is there a burglar?

Variables: $Burglar$, $Earthquake$, $Alarm$, $JohnCalls$, $MaryCalls$
Network topology reflects "causal" knowledge:

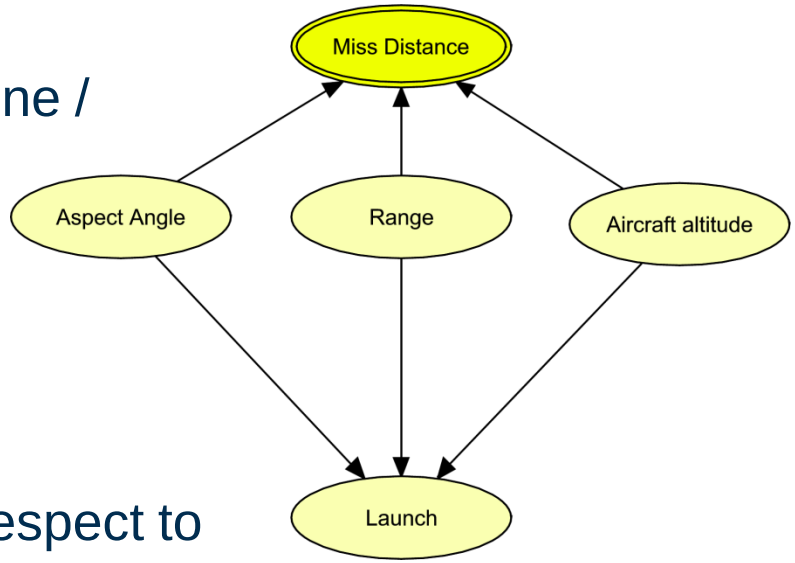
- A burglar can set the alarm off
- An earthquake can set the alarm off
- The alarm can cause Mary to call
- The alarm can cause John to call

Miss Distance Data Fusion – Bayesian Networks



Miss Distance Data Fusion – Bayesian Networks

- Aircraft vulnerability depends on
  - **Probability** of missile launch (doctrine / training), and
  - Miss distance **if launched**
- Both have complex dependencies

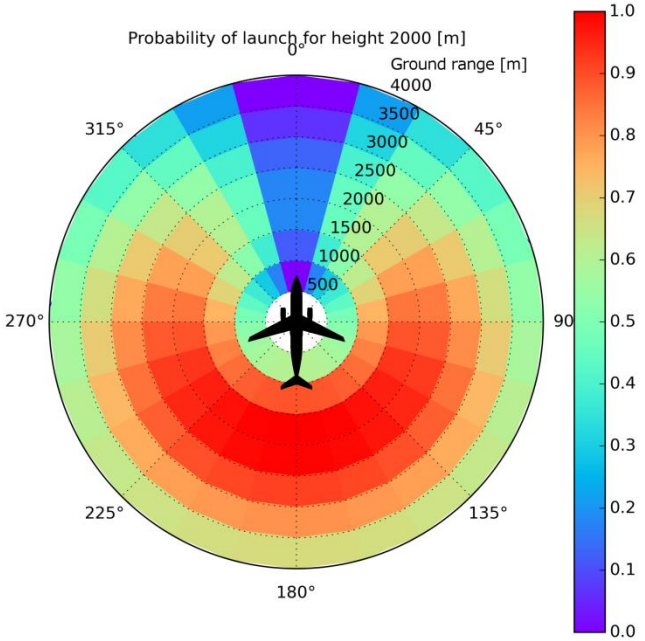


- **Simple** model
  - Launch location aspect angle with respect to aircraft
  - Range between launch location and aircraft
  - Aircraft height above missile location

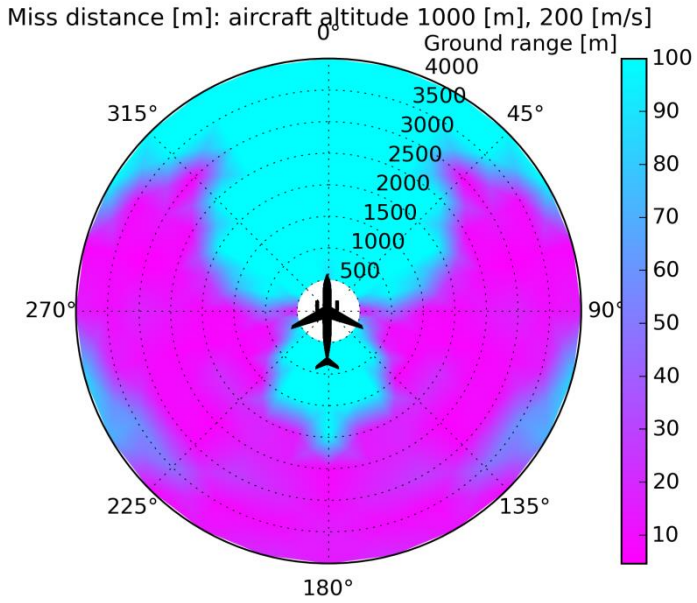
- A real-world production model has many more inputs

Miss Distance Data Fusion – Bayesian Networks

Probability of missile launch



Miss distance



- Training & doctrine
- Human **expert panel**
- This example by math model

- Simulation calculation

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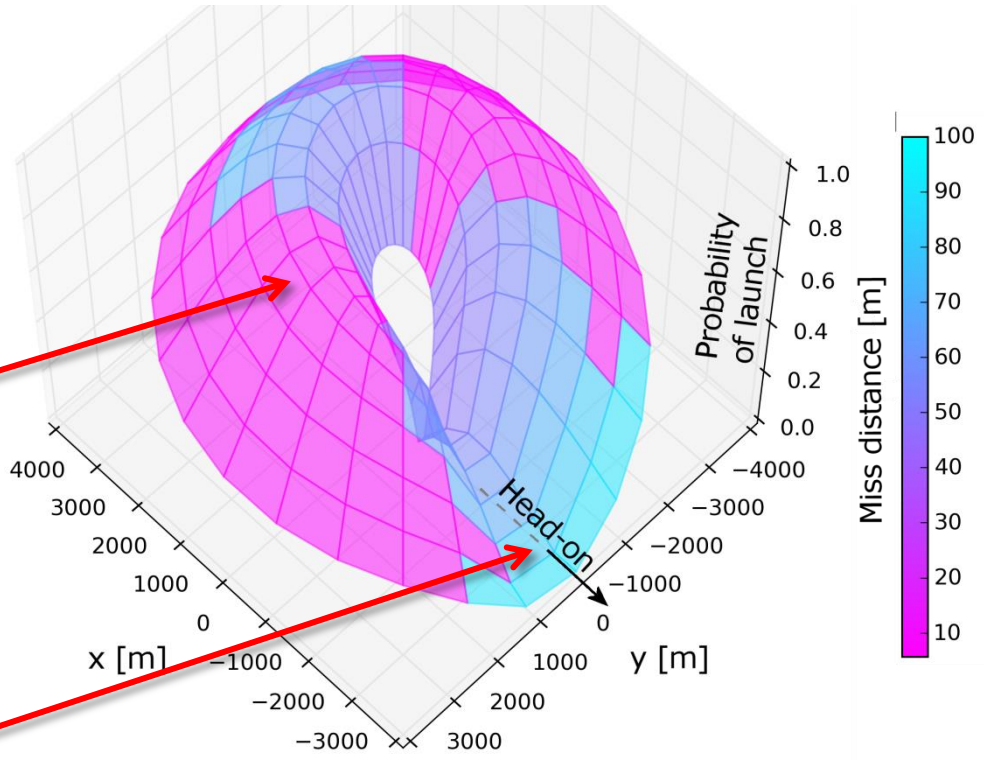
Miss Distance Data Fusion – Bayesian Networks

Simplistic and naïve approach combines the data:

- z-height: launch probability
- colour: miss distance



- **High danger zones**: magenta hills (small R_{miss} and high P_{launch})
- **Intermediate zones**: cyan hills & magenta valleys.
- **Safest zones**: cyan valleys (large R_{miss} and low P_{launch})

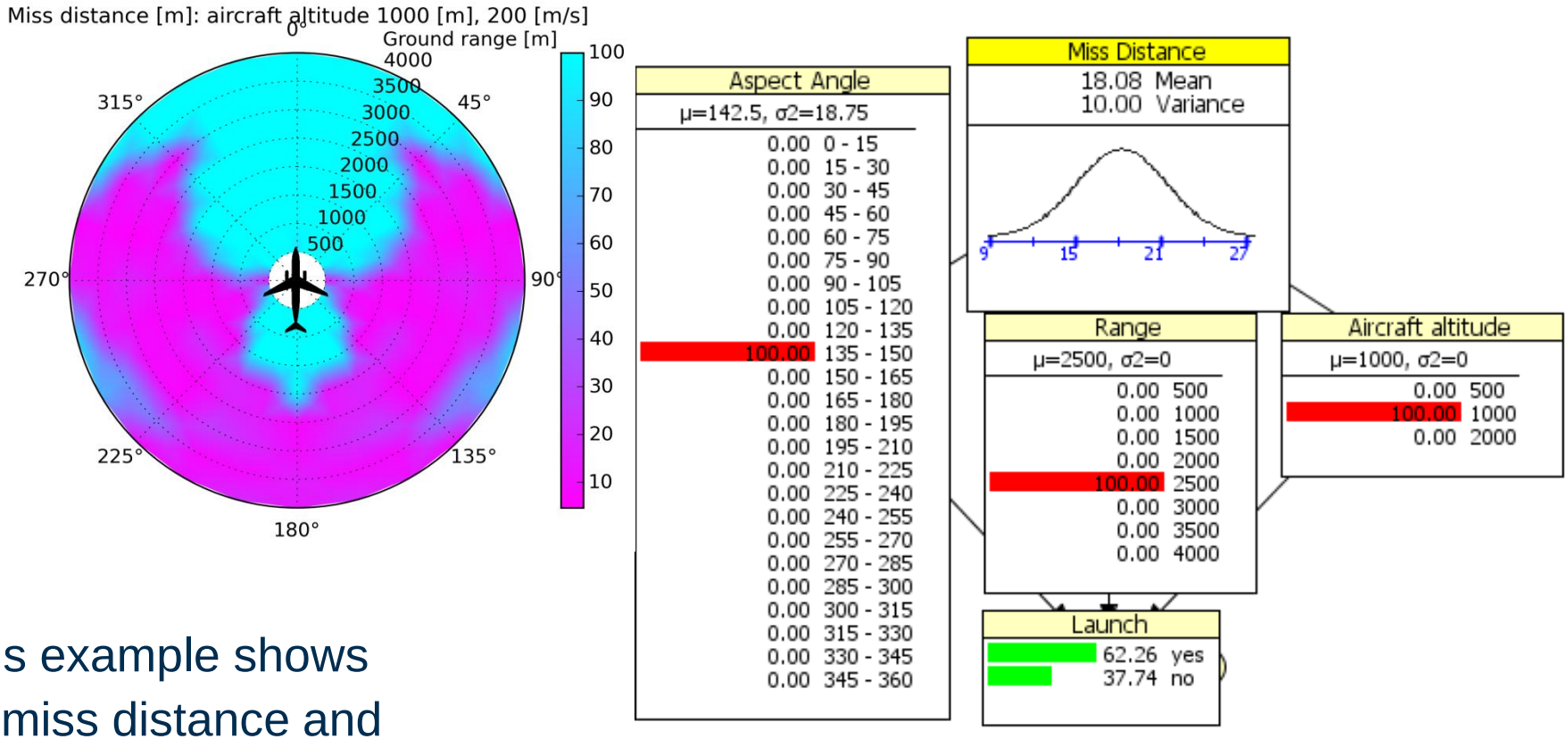
Miss Distance Data Fusion – Bayesian Networks

- Hugin BN modelling software
  - Developed specifically to develop BN for decision making
  - GUI
  - Inference Engine
    - Predictive Mode (top-down)
    - Prescriptive Mode (best state)
    - Diagnostic Mode (bottom-up (what if))

- Statistician
  - Dr Alta de Waal

Miss Distance Data Fusion – Bayesian Networks

Bayesian network provides **prediction** views on data



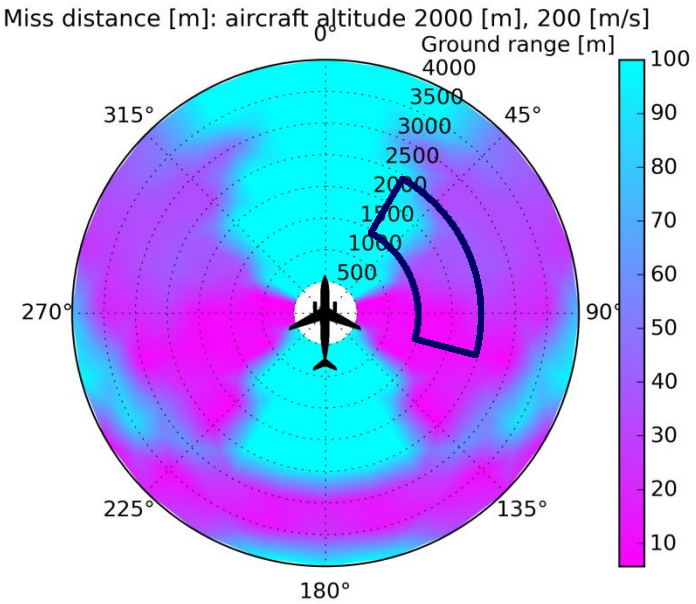
This example shows

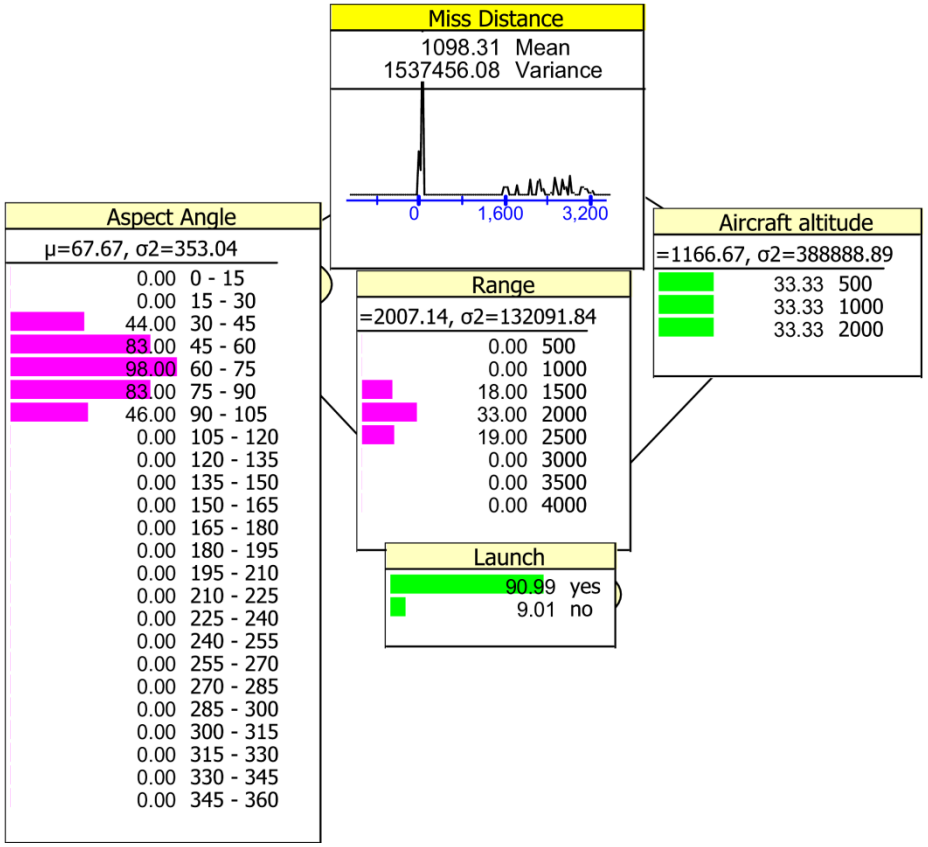
- miss distance and
- launch probability

for single launch location

Miss Distance Data Fusion – Bayesian Networks

Bayesian network provides likelihood views on data





This example shows

- miss distance and
- launch probability
- likely aircraft altitudes

for a launch area defined by

- aspect angle and
- range

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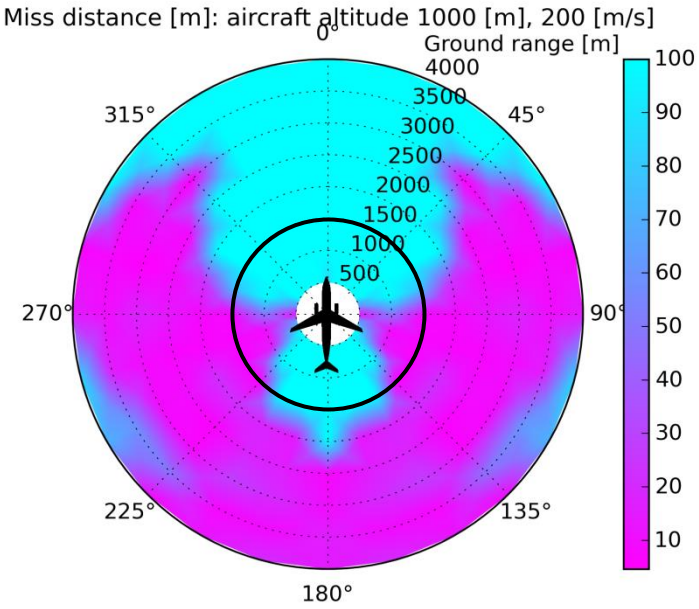
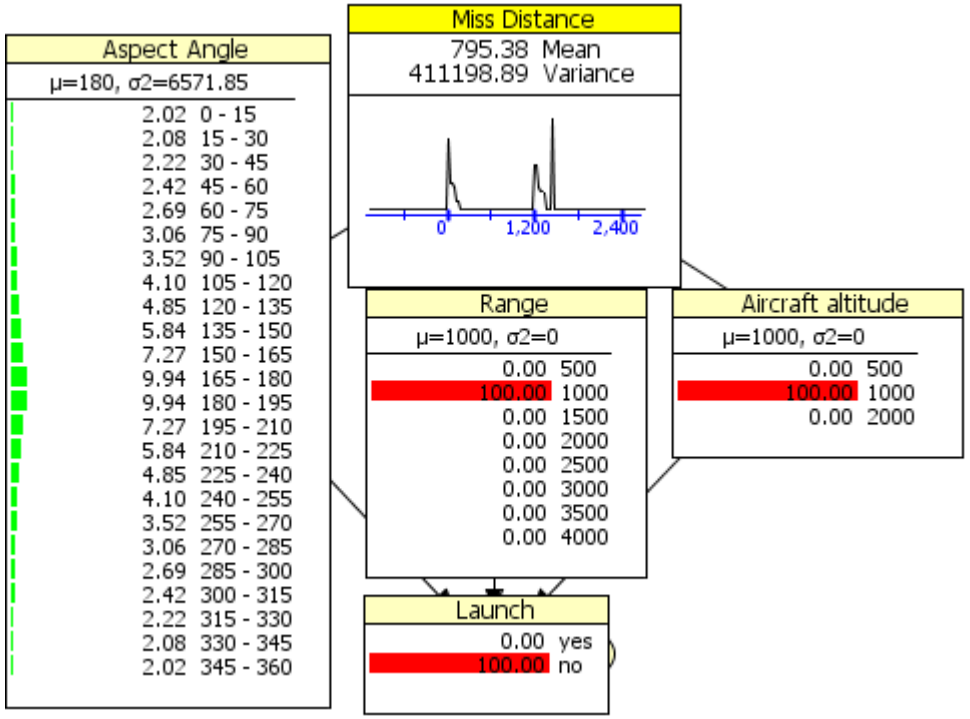
Miss Distance Data Fusion – Bayesian Networks

Bayesian network provides aggregate inference views on data





This example shows

- miss distance and
- likely aspect angles

for ‘no launch’ at given range and altitude

Conclusion

- Aircraft signatures can be modelled accurately
- Optical signatures are **critically affected by**
  - Sun reflection
  - Background radiance

- The **aircraft-missile engagement is a complex series of events**, many of which are only partially understood

- Bayesian Network model developed as a **proof-of-concept**
- Provides **high-level**, aggregated platform vulnerability information
- Decision Support Modelling Tools – not published

Further Work

- Extend the BN model to include other variables (increase the complexity)
- These inputs to be simulated (miss distance prediction)
- Model validation
  - System specifications
  - Operational experts (broader)
- “Proper design process”

- Desktop tool

Thank You

Kevin Gopaul
kgopaul@csir.co.za

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