IDA

Active Denial Technology Computational Human Effects End-To-End Hypermodel (**ADT CHEETEH**)

Shelley Cazares, Jeffrey A. Snyder, Jim Belanich, John Biddle,
Allyson Buytendyk, Stacy Teng, Kelly O'Connor

Institute for Defense Analyses (IDA)
Alexandria, VA, USA

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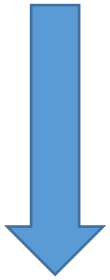
IDA Challenges in Modeling Non-Lethal Weapons

	Traditional (Lethal) Weapon	Non-Lethal Weapon
Intended Use of Weapon:	Permanently destroy target	Temporarily incapacitate target
Goal of Model:	Estimate weapon effect on target: • Physical • Physiological	Estimate weapon effect on target: • Physical • Physiological • ***Cognitive*** • ***Behavioral***



Increased Variability & Uncertainty

Despite these challenges:
We developed an end-to-end computational model of a NLW system

Active Denial Technology (ADT)

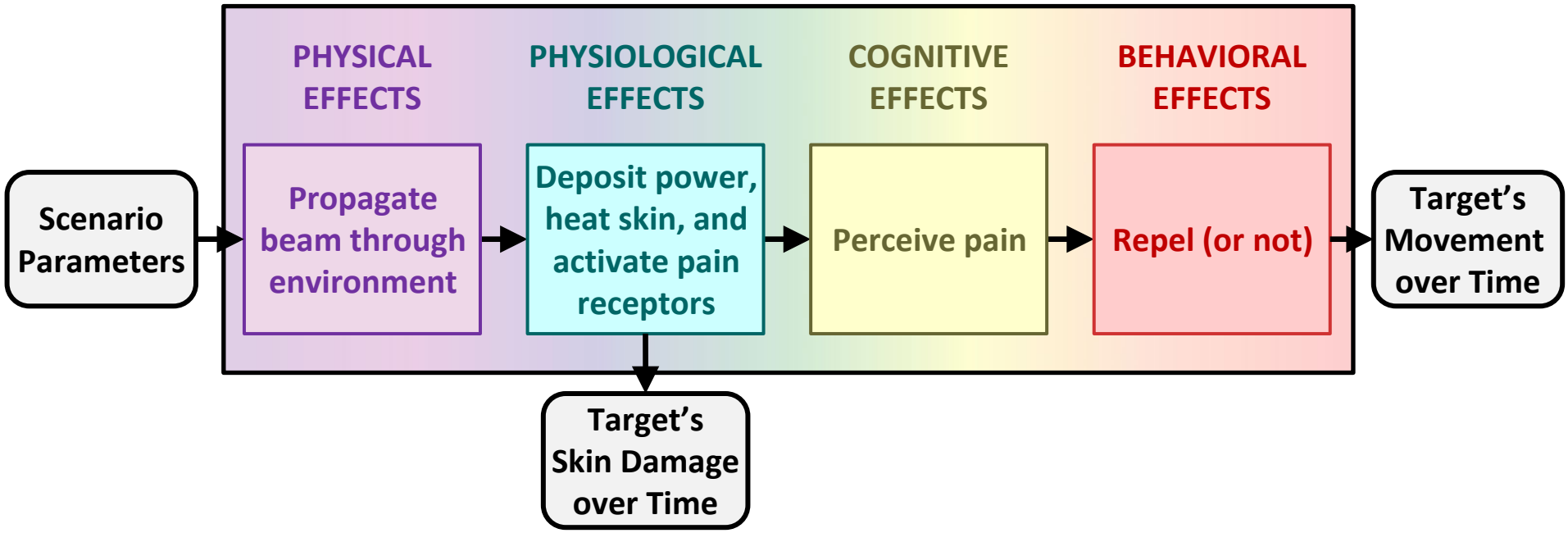
Photo By: Lance Cpl Andrew Huff (2017)

- **Counter-personnel NLW system:**
  - Crowd control
  - Patrol and convoy protection
  - Perimeter security
- **Emits short-duration pulses of focused 95 GHz electromagnetic energy**
- **Energy diffuses ≈400 microns into target's skin**
  - Produces **no skin damage** within appropriate range of doses
  - Elicits **burning sensation strong enough to repel**, i.e., to compel target to immediately flee

The ADT system is a NLW system to stop, deter, and turn back suspicious individuals

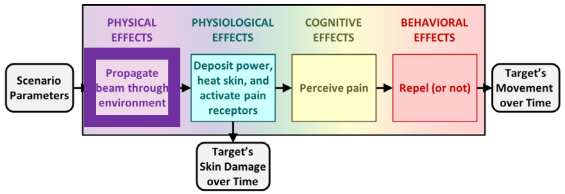
JNLWD (2016) Active Denial Technology Fact Sheet.
https://jnlwp.defense.gov/Portals/50/Documents/Press_Room/Fact_Sheets/ADT_Fact_Sheet_May_2016.pdf

ADT CHEETEH: Active Denial Technology Computational Human Effects End-To-End Hypermodel



ADT CHEETEH consists of four main components to model an ADT encounter with a human target

IDA **ADT CHEETEH:** Physical Effects



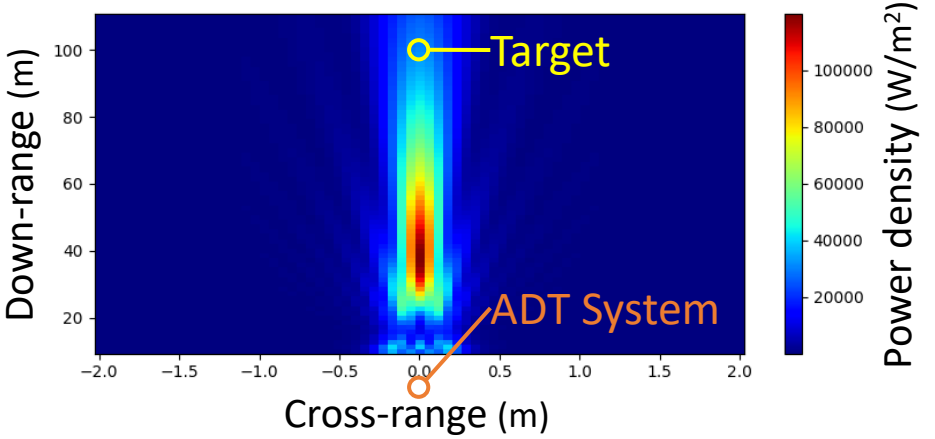
What: Power density in space and on target

How:

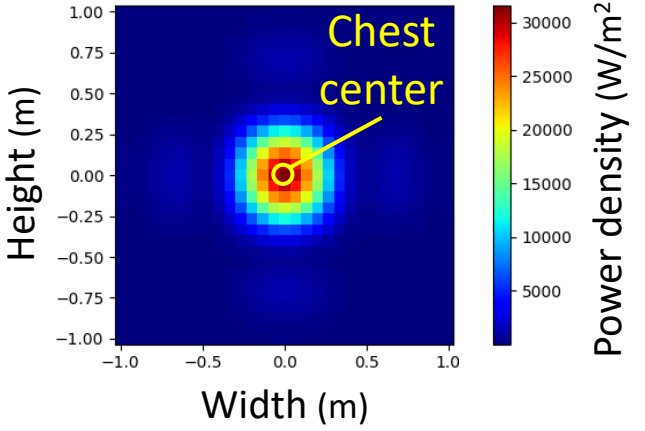
1. Treat ADT system as array of elements (Orfanidis 2002, Balanis 2005)
3. Estimate how energy propagates from each element through environment (Liebe 1993, Stutzman 2012)
3. Sum over all elements at target (Orfanidis 2002, Balanis 2005)

$$\boldsymbol{E}(\boldsymbol{r}) = \sum_{i=0}^{N-1} \beta_i \sqrt{2\eta_0 \wp_i} \frac{e^{\left(-\frac{\alpha}{2}R_i - jkR_i\right)}}{4\pi R_i} \boldsymbol{f}\left(\hat{\boldsymbol{R}}_i\right), \quad P(\boldsymbol{r}) = \frac{|\boldsymbol{E}(\boldsymbol{r})|^2}{2\eta_0}$$

Power density in space (bird's eye view)

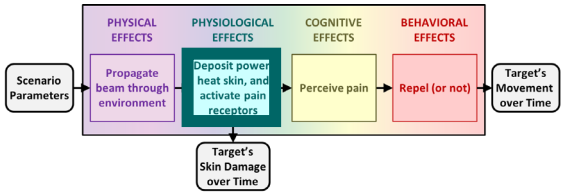


Power density on target (incident view)



The ADT CHEETEH physical component estimates how the ADT power propagates through the environment

IDA ADT CHEETEH: Physiological Effects (1 of 3)



What: Power density in skin

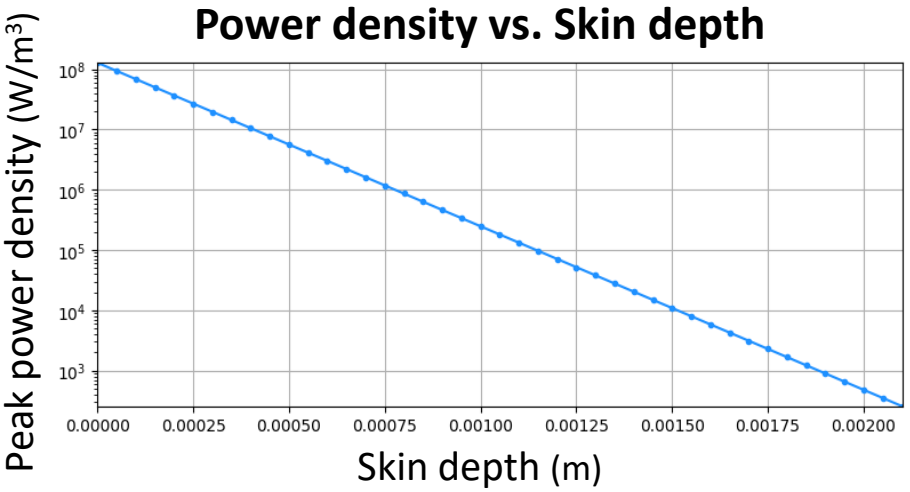
How:

1. Estimate how much incident power is reflected off of target's skin surface (Walters 2000)

$$P_{\text{dep}}(\boldsymbol{r}) = (1-\gamma)P(\boldsymbol{r})$$

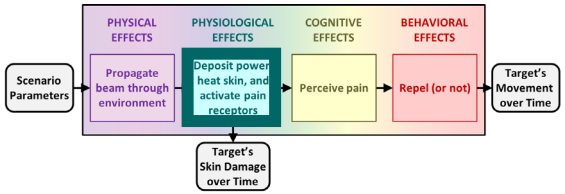
2. Estimate how deep the remaining power deposits under target's skin surface (Welch 1995, Walters 2000)

$$q(\boldsymbol{r}, y) = \mu P_{\text{dep}}(\boldsymbol{r}) e^{-\mu y}$$



The ADT CHEETEH physiological component first estimates how the incident ADT power deposits into the target's skin

IDA ADT CHEETEH: Physiological Effects (2 of 3)



What: Temperature and damage in skin

How:

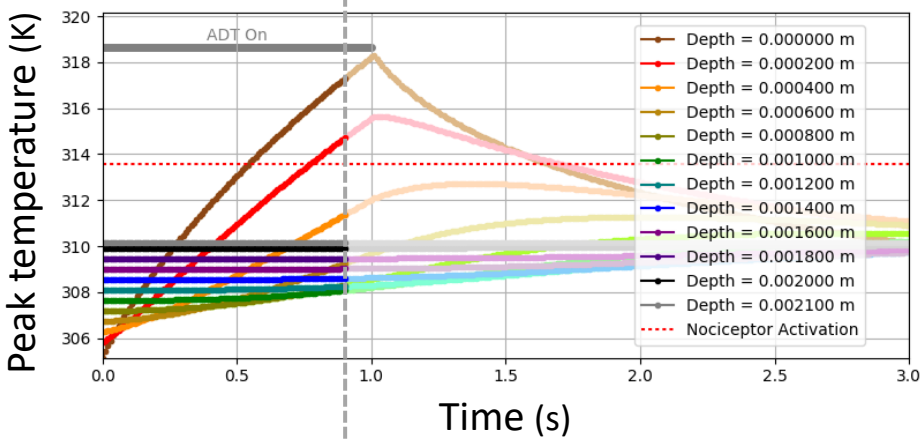
1. Estimate how fast and deep heat transfers through target's skin (Fourier 1822, Cannon 1984, Haberman 1983, Rushmer 1966, Koehler 1996, Xu 2010)

$$\rho C_p \frac{\partial T(\boldsymbol{r},y,t)}{\partial t} = \frac{\partial}{\partial y}\left(K \frac{\partial T(\boldsymbol{r},y,t)}{\partial y}\right) + q(\boldsymbol{r},y)$$

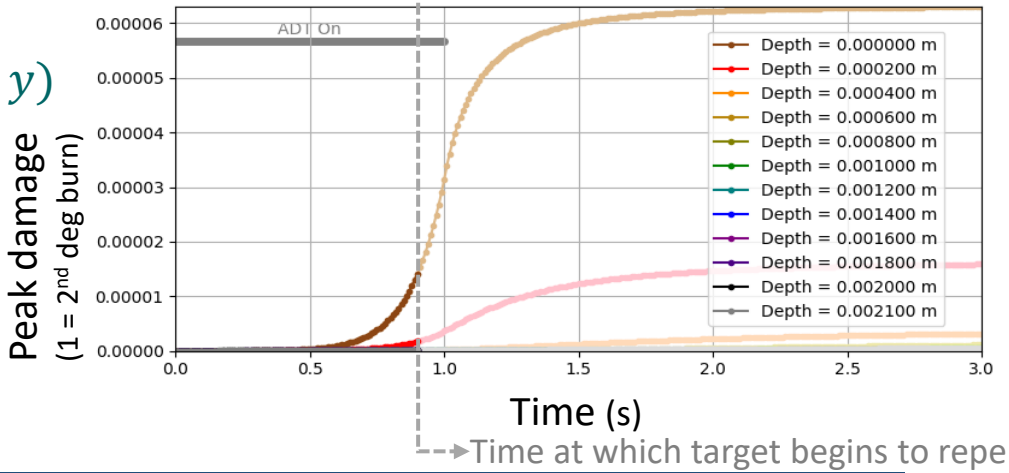
2. Estimate how much the heat destroys proteins in target's skin (Henriques 1947, Pearce 2010)

$$\Omega(\boldsymbol{r},y,t) = \int_0^t A e^{\left(\frac{-E_a}{R\,T(\boldsymbol{r},y,\tau)}\right)} d\tau$$

Temperature vs. Time

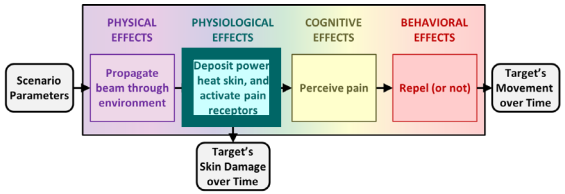


Damage vs. Time



The ADT CHEETEH physiological component then estimates how heat transfers through the target's skin and (possibly) causes damage

IDA ADT CHEETEH: Physiological Effects (3 of 3)

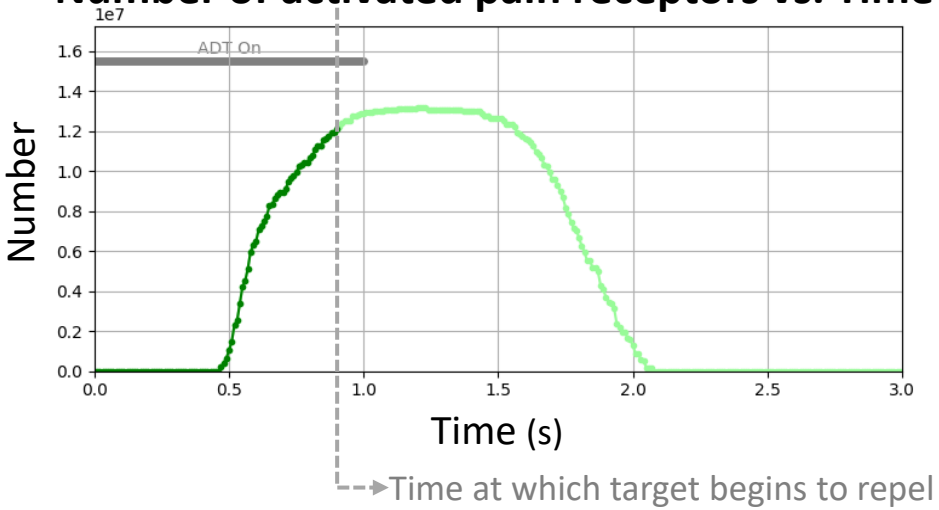


What: Number of activated pain receptors

How:

1. Treat skin as collection of voxels (3D pixels)
2. Estimate number of pain receptors in each voxel, based on their density (Ochoa 1969, Schmidt 1995, Tillman 1995, McArthur 1998, Sandby-Moller 2003)
3. Estimate average temperature of each voxel
4. If voxel's average temperature ≥ threshold (Tillman 1995), then assume all pain receptors are activated in voxel
5. Sum over all voxels

Number of activated pain receptors vs. Time

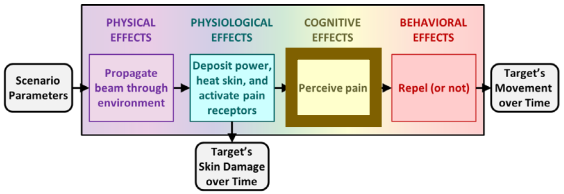


$$x_i(t) = \begin{cases} V_i \rho_{\text{noc}}, & if\ \bar{T}_i(t) \geq T_{\text{act}} \\ 0, & if\ \bar{T}_i(t) < T_{\text{act}} \end{cases}$$

$$x(t) = \sum_{i=0}^{M-1} x_i(t)$$

The ADT CHEETEH physiological component also estimates how many pain receptors become activated in the target's skin

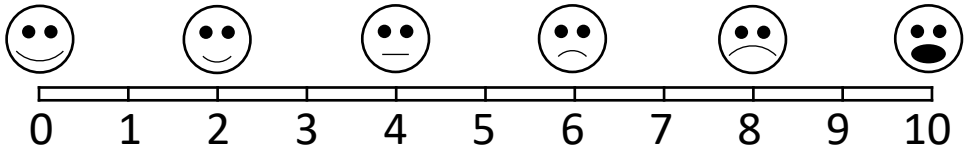
ADT CHEETEH: Cognitive Effects



What: Perceived pain level

How:

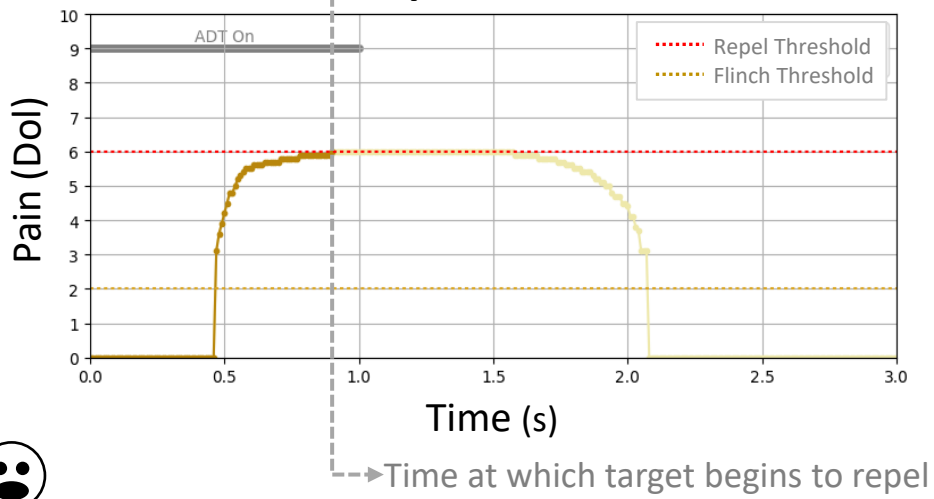
1. Quantify pain on Dol scale (Hardy 1947, 1948):



2. Translate number of activated pain receptors to perceived pain level, based on S-shaped curve fit to data in scientific literature (Hardy 1947, Mouraux 2012)

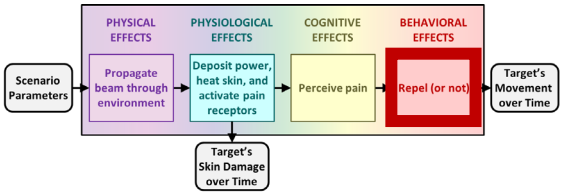
$$y(t) = \frac{a}{1 + e^{-\left(\frac{\log(x(t)) - b}{c}\right)}}$$

Perceived pain level vs. Time



The ADT CHEETEH cognitive component estimates the target's perceived pain level

IDA ADT CHEETEH: Behavioral Effects

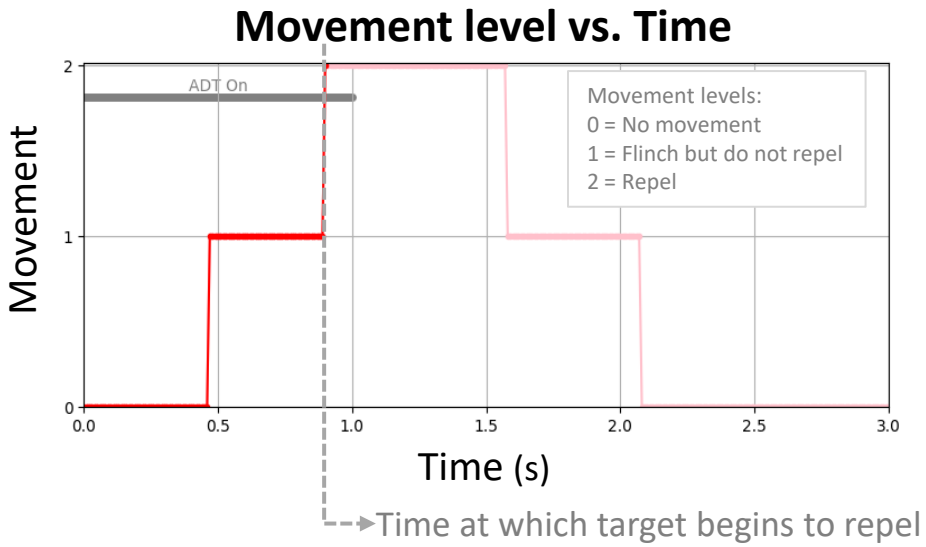


What: Movement levels over time

0 = No movement

1 = Flinch but do not repel

2 = Repel



How:

1. Modulate perceived pain level based on motivation

$$y'(t) = y(t) - \frac{m}{m_0}$$

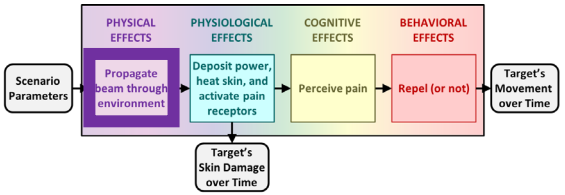
2. Compare motivation-modulated pain to pain tolerance thresholds (Xu 2008, Plaghki 2010, Short 2010, Moreno 2012, Mouraux 2012)

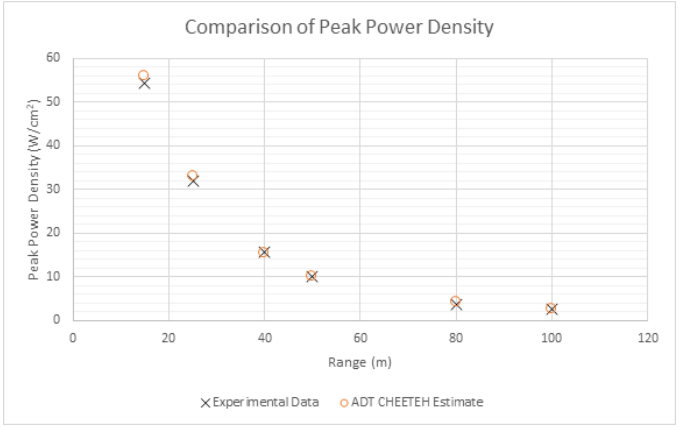
$$g(t) = \begin{cases} 0, if\ y'(t) < Y_{\text{lo}} \\ 1, if\ y'(t) \geq Y_{\text{lo}}\ and\ y'(t) < Y_{\text{hi}} \\ 2, if\ y'(t) \geq Y_{\text{hi}} \end{cases}$$

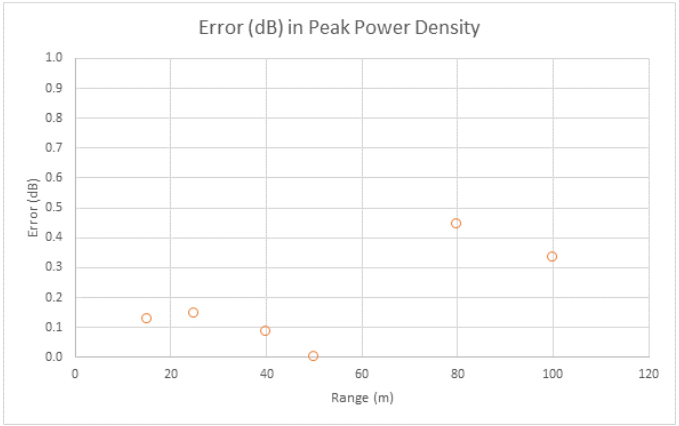
The ADT CHEETEH behavioral component estimates when the target (possibly) repels

IDA **ADT CHEETEH:** Verification & Validation

- **Verification:** Full
  - Compared manual vs. model calculations for all output parameters
  - All errors ≈0
- **Validation:** Partial
  - Validation data was only available for output parameter of physical component – ***power density on target***:
    - **ADT CHEETEH estimates were within 0.5 dB of experimental data**
    - We conclude the ADT CHEETEH physical component passed its validation test
  - We are exploring opportunities to obtain validation data for the three other ADT CHEETEH components



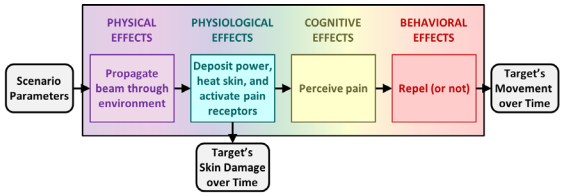




Biddle et al. (2018) *Beam Propagation Model Selection for Millimeter-Wave Directed Energy Weapons*. Presented at the Directed Energy Systems Symposium, 24-27 Sept 2018.

Full validation of ADT CHEETEH is necessary and on-going

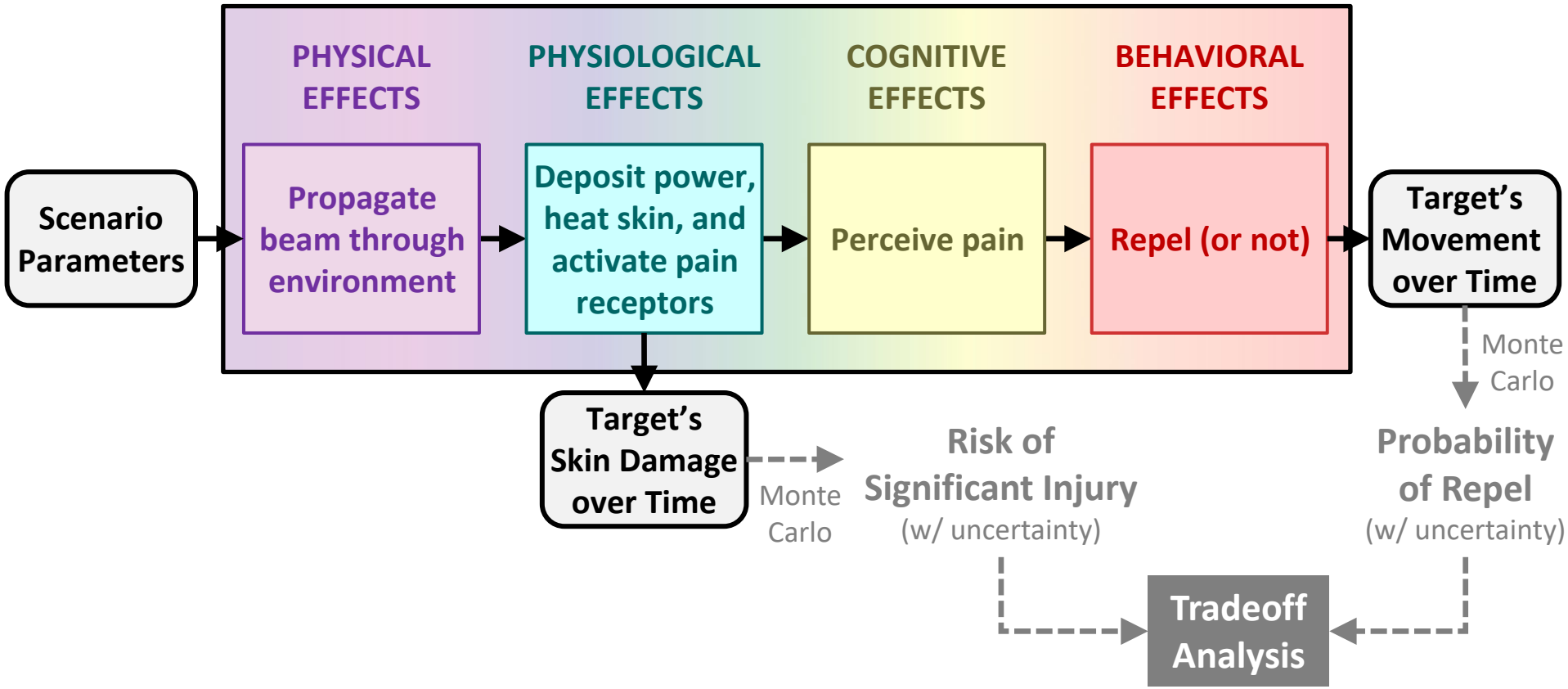
IDA **ADT CHEETEH:** Sensitivity Analysis



- **Purpose:** Identify to which factors of a scenario is ADT CHEETEH most sensitive
- **Methods:**
  - Perform thousands of runs of ADT CHEETEH
  - Vary individual input parameters over ±1 standard deviation
  - Examine ADT CHEETEH's final output parameter – movement level over time
  - Identify those input parameters whose variation caused the movement level to "max out" at all three possible values (0, 1, or 2)
- **Results:** Four noteworthy input parameters:
  - ***ADT pulse duration*** – in control of ADT system developers
  - ***Target's skin surface reflectivity*** – subject to natural variation in target population – well understood
  - ***Temperature threshold at which pain receptors activate*** – subject to natural variation in target population – partly understood
  - ***Density of pain receptors*** – subject to natural variation in target population – not well understood, in this context

Once validated, ADT CHEETEH could help prioritize which factors of an ADT encounter could benefit from further research

IDA ADT CHEETEH: Monte Carlo Plans



Once validated, ADT CHEETEH could be used to explore the trade space between Risk of Significant Injury and Probability of Repel

IDA Conclusion

- ADT CHEETEH is a **computational, end-to-end model** of the physical, physiological, cognitive, and behavioral effects of the ADT system on a human target
- All four components of ADT CHEETEH **passed all verification tests** (errors ≈0)
- Validation data was only available for the physical component model:
  - The **physical component passed its validation test** (errors < 0.5 dB)
  - We are exploring opportunities for obtaining data to validate the other components (using FLIR cameras, pain surveys, triggered timers/video, etc)
- We used ADT CHEETEH to **explore the most noteworthy factors** in an ADT encounter
  - Some within control of the ADT system designer (pulse duration)
  - Others subject to natural variation in target population (skin reflectivity, temperature activation threshold, pain receptor density)
- Once validated, ADT CHEETEH could **support force-on-force simulation software**:
  - Simulations have friendly, opposing, and neutral forces with variable weapon sets
  - Data tables stipulate a weapon's Probability of Effect on a target
  - ADT CHEETEH could be used to build data tables to simulate ADT effects

IDA References (1 of 2)

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IDA References (2 of 2)

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Questions?

Shelley Cazares

Institute for Defense Analyses

Alexandria, VA, USA

+1 703 845 6792

scazares@ida.org

More details are published in the peer-reviewed scientific literature:
https://link.springer.com/article/10.1007/s41314-019-0023-7