Valuing ISR Resources

Tod S. Levitt[*], Kellen G. Leister[*], Ronald F. Woodaman[*], Jerrit K. Askvig[*],
Kathryn B. Laskey[*], Rick Hayes-Roth[†], Chris Gunderson[†]

[*]George Mason University C4I Center
[†]Naval Postgraduate School

May 25, 2011

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept

- VIR Technology Innovations

VIR Objectives

- Develop a real-time method for allocating netcentric plug-and-play tactical collection assets
  - Adapt and optimize for missions
  - Account for evolution of tactical red and blue situation
  - Provide a smart-push of information to the warfighter

- Make the methodology consistent across the military value-chain enterprise
  - Support acquisition, deployment and operation with a uniform and scientifically sound technical approach
  - Develop a common core algorithmic approach

VIR Conceptual Approach

- Work backwards from operations to deployment to acquisition

- Operations: address complexity and optimization of alternative linkages of netcentric assets in a single area of operations

- Deployment: optimization over N area of operations accounting for mission priorities

- Acquisition: add cost of assets into optimization and do what-if simulation by iterating alternative deployments/operations

VIR Technical Approach

- Develop algorithms to
  - allocate a set of ISR assets across a set of FOBs; and
  - determine emplacement of the ISR assets within each FOB's operating area

- Such that the global effect is to maximize the value of received information per cost according to
  - tactical scenarios of interest, threats and associated conditions of interest, cost of assets

- Prototype the capability and perform experiments to determine
  - practical limitations and additional requirements of methodology implementation
  - scalability across ISR assets and number of FOBs

- Focus on RPV tactical scenarios: C-IED, ambush and HVI

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept

- VIR Technology Innovations

COIs and ACs

- Condition of interest (COI) is an incident of:
  - IED emplacement (I)
  - Ambush in preparation (A)
  - High value individual in FOB operating region (H)

- Admissible configuration (AC) of ISR assets is:
  - set of ISR assets
  - sequential workflow of those assets
  - that can detect a COI
  - and report the COI detection, i.e. have it brought to the attention of a warfighter

ISR Assets

Asset	Description
GBOSS	Tower
GBOSS Lite	Mini tower
Shadow/LEAP	Unmanned aerial vehicle (UAV)
MSIDS	Video sensor
UGSS	Seismic, acoustic & magnetic vehicle detector and counter
IRID II	IR intusion detector
Night Imager	EO and IR detection triggered image capture
MASF	EO detection and multiple-capability communications interface
ADDT	Dismount detector
AECT	Biometric recognition
Comm	Hard wire or radio
RR	Radio repeater
VS	Video Scout
SMSS	Mobile manned ground platform

Admissible Configurations

COI Key →	A: Ambush I: IED H: HVI							
Sensor Key →	MSIDS: video UGS: seismic, acoustic & magnetic vehicle detector and counter							
	IRID: IR intrusion detector Night Imager: EO and IR detection-triggered image capture							
Exploitation Key →	MASF: Detect and Comm ADDT: Dismount Detector AECT: Biometric Recognition							
Communications Key →	Comm: hard wire or radio MASF: radio RR: Radio Repeater							
Report Key →	User: Human Operator SMSS: Mobile Manned Ground Platform							
	VS: Video Scout UAV Manned Hand-Portable Downlink							

COI	AC#	Component								
		1	2	3	4	5	6	7	8	9
A, I, H	1	GBOSS	User							
A, I, H	2	GBOSS Lite	User							
A, I	3	Shadow/LEAP	VS	VS	VS	VS	VS			
A, I	4	Shadow/LEAP	SMSS							
A, I, H	5	MSIDS	User							
A, I	6	UGS	Comm	SMSS						
A	7	IRID	Comm	SMSS						
A, I, H	8	Night Imager	Comm	SMSS						
A, I	9	UGS	MASF	SMSS						
A	10	IRID	MASF	SMSS						
A, I, H	11	Night Imager	MASF	SMSS						
A, I	12	Night Imager	ADDT	Comm	SMSS					
H	13	Night Imager	AECT	Comm	SMSS					
A, I	14	UGS	MASF	Comm	Night Imager	Comm	SMSS			
A, I	15	UGS	MASF	Comm	Night Imager	ADDT	Comm	SMSS		
A, I, H	16	Night Imager	MASF	SMSS	Shadow/LEAP	VS	VS	VS	VS	VS
A, I	17	Night Imager	ADDT	Comm	Shadow/LEAP	SMSS				
A, I	18	Night Imager	ADDT	Comm	Shadow/LEAP	VS	VS	VS	VS	VS
A, I	19	UGS	MASF	Comm	Night Imager	ADDT	Comm	Shadow/LEAP	SMSS	
A, I	20	UGS	Comm	RR	Comm	SMSS				
A	21	IRID	Comm	RR	Comm	SMSS				
A, I, H	22	Night Imager	Comm	RR	Comm	SMSS				
A, I	23	UGS	MASF	RR	Comm	SMSS				
A	24	IRID	MASF	RR	Comm	SMSS				
A, I, H	25	Night Imager	MASF	RR	Comm	SMSS				
A, I	26	Night Imager	ADDT	Comm	RR	Comm	SMSS			
H	27	Night Imager	AECT	Comm	RR	Comm	SMSS			
A, I	28	UGS	MASF	Comm	RR	Comm	Night Imager	Comm	SMSS	
A, I	29	UGS	MASF	Comm	RR	Comm	Night Imager	ADDT	Comm	SMSS

Detection & Reporting Probability Model

- Determination of ISR value requires estimating probabilities that:
  - admissible configuration *ac* assigned to surveillance zone *sz* in time period *Δt*
  - will detect and report incident *i* of COI type *c* (e.g., IED emplacement) given that *i* occurs.

- Expressed as $P_{c, ac, sz, \Delta t}$

- Presence of several factors (terrain, time of day, etc.) affecting detection probabilities requires use of probability models to estimate **P** values

- Bayesian network used to model probability distributions for each admissible configuration

- Bayesian Network links together and does inference across multiple conditional probabilities to arrive at marginal probability that *ac* detects and reports incident *i* in *sz* during specified time interval, given that the incident occurs:
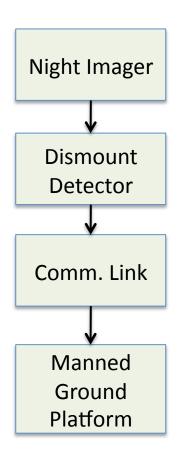
  - **P(component #1 of *ac* triggers* | incident i occurs) for *ac assigned to sz***

  - **P(component *n* of *ac* triggers | component *n-1* triggers) for each component *n* of *ac assigned to sz***

  *triggers = receives signal, performs function, and sends signal

- Probability that each component of *ac* triggers properly can be affected by terrain, distance from *sz*, human or mechanical error, etc.

- Overall probability that incident *i* is detected and reported is the joint probability that all components function properly for the *ac* watching for the COI in *sz* when *i* occurs
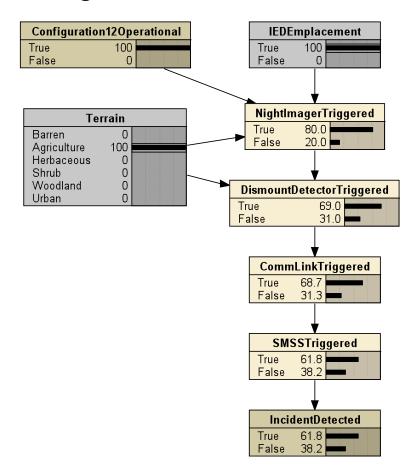
AC Workflow
to Bayesian Network

Asset Configuration #12

Bayesian Network Detection Probability
in Agricultural Surveillance Zone

Night Imager

↓

Dismount Detector

↓

Comm. Link

↓

Manned Ground Platform

Configuration12Operational

True	100
False	0

IEDEmplacement

True	100
False	0

Terrain

Barren	0
Agriculture	100
Herbaceous	0
Shrub	0
Woodland	0
Urban	0

NightImagerTriggered

True	80.0
False	20.0

DismountDetectorTriggered

True	69.0
False	31.0

CommLinkTriggered

True	68.7
False	31.3

SMSSTriggered

True	61.8
False	38.2

IncidentDetected

True	61.8
False	38.2

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

→ - Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept

- VIR Technology Innovations

Continuous IPB:
The Threat Stochastic Process (TSP)

- TSP summarizes a priori expectation of likely locations of relevant red threat activities for a period of time going forward
  - Mathematical representation is a marked point (stochastic) process (MPP) where a "mark" is equivalent to a COI, and a mark instance is a COI instance
  - MPP representation of TSP for intelligence preparation of the battlespace (IPB) is a technical innovation that aims at scientifically sound continuously updatable IPB

- TSP is fundamentally spatial, i.e. geographic, incorporating
  - terrain features: elevation, ground cover, hydrology, roads, etc. as they affect red's preference for sites to perpetrate threat incident (e.g. where to emplace IED)
  - history of red threat activities and incidents (e.g. IED emplacements, ambushes)
  - red location estimates (e.g. populations, camps, safe houses, red logistical stores, etc.)
  - blue operations plans (usually at a general level)

- The relative likelihood of an attack in any given zone determined based the factors: Blue Force presence, Red Force Presence, and Terrain Suitability

TSP Red & Blue Factors

- **Blue Force Presence** - Attacks can only occur if Blue Forces are present - degree blue forces will be present relative to surrounding locations without using historical data estimated by:

    - Distance from FOB - There is more blue force activity near FOBs
    - Road type and road network density - Larger roads are use more frequently by blue forces and areas with many roads have a better chance of blue activity than areas with fewer roads

- **Red Forces Presence** - Red Forces do not want to travel large distances to conduct attacks

    - Areas with a larger number of red forces have a higher probability of attack vs. areas with a smaller amount of red forces
    - Different local population types contain different numbers of red forces

TSP Terrain Suitability
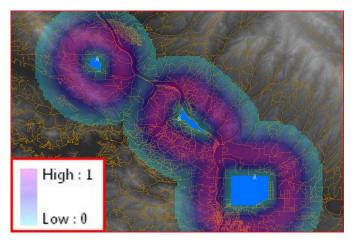
- Suitability of a zone for an action from Red's perspective based on the zone's terrain features

  - Vegetation type - Red forces prefer placement locations that have concealment

  - Preferred Emplacement Locations - Red Forces prefer locations such as culverts, bridges, intersections, etc.

  - Blue force vehicle speed - Slower Blue vehicle speed is preferred by Red because it increases the probability of an accurate attack

  - Elevation difference – IED and Ambush activities better when monitoring / attack can be conducted from above
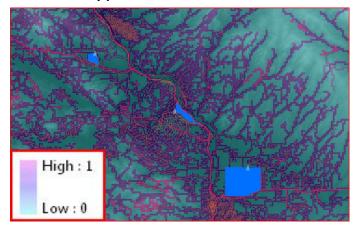
IED TSP: Blue Force Presence

Distance from FOB

Road Type
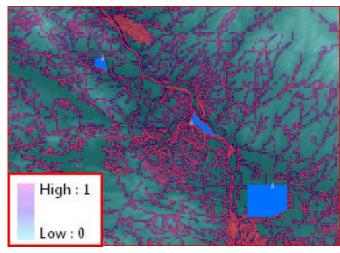
Road Density
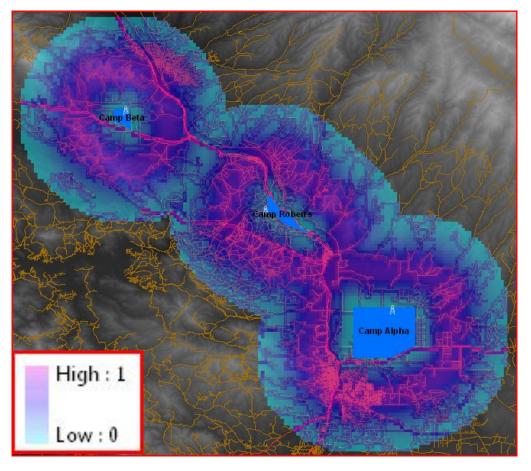
IED TSP: Blue Force Presence

Blue Force Presence Total

Blue Force Presence Total =
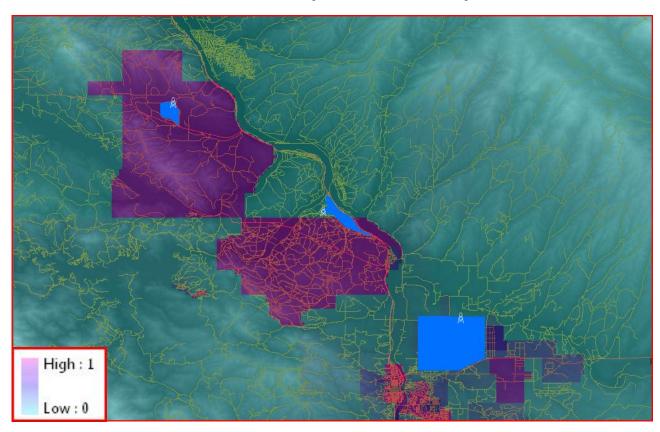
Distance from FOB + Road Type + Road Density

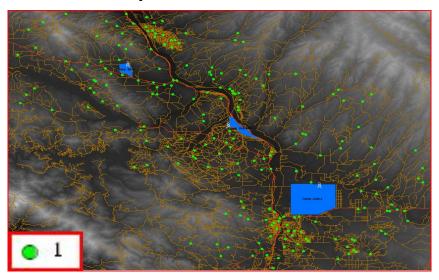# IED TSP: Red Force Presence

Red Force Population Density
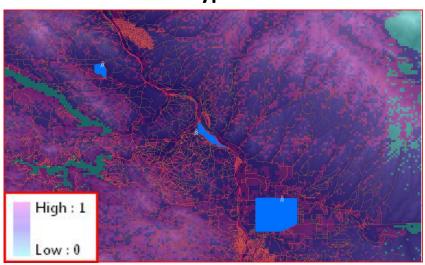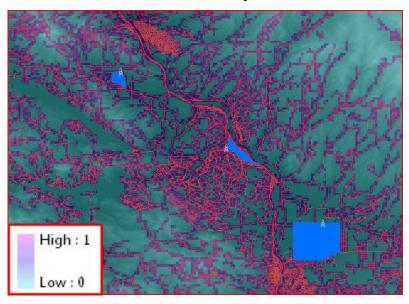
IED TSP: Terrain

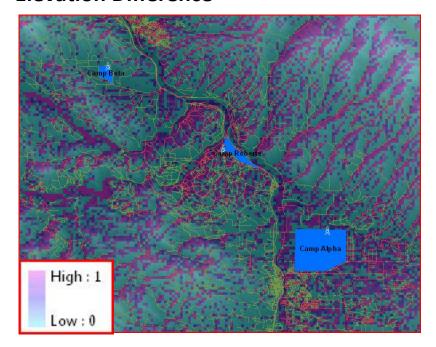**Terrain Type**

Preferred Emplacement Locations

IED TSP: Terrain (2)

Blue Force Vehicle Speed

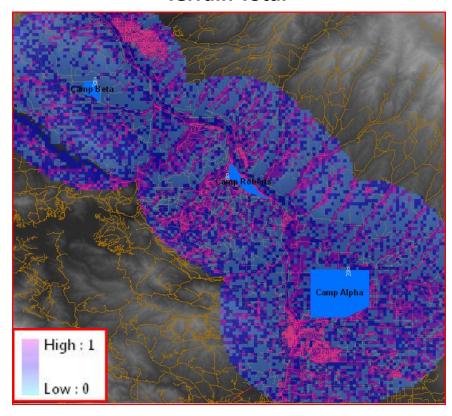**Elevation Difference**
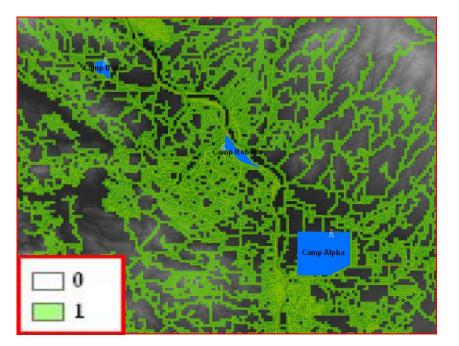
IED TSP: Terrain (3)

Terrain Total

Terrain Total =   Terrain Type + Preferred Emplacement Locations
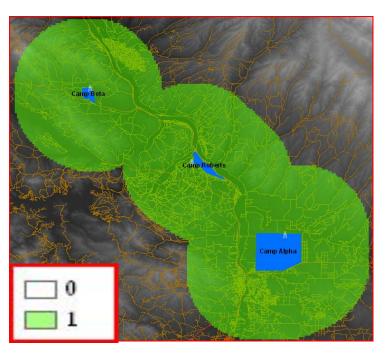**+ Blue Vehicle Speed + Elevation Difference**

IED TSP: Region Limits
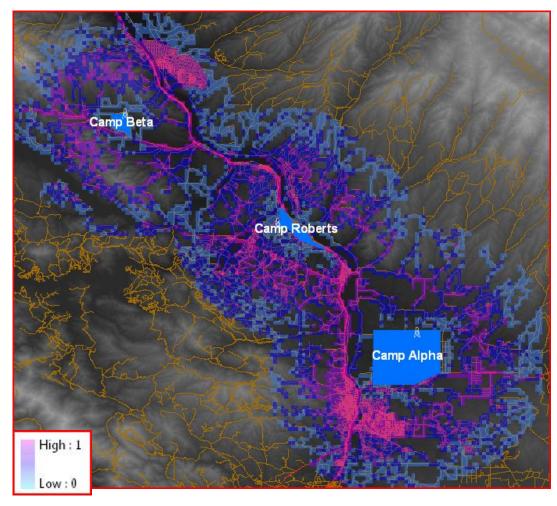
Is Road

Is Radius

To remove unnecessary zones the final sum is multiplied by an "Is Road" and "Is Radius" boolean value (i.e. zero or one)

IED TSP

IED TSP Total

IED TSP Total = (Blue Force Presence Value + Red Force Presence Value + Terrain Value)
* IsRoad * IsRadius

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

→ - Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept

- VIR Technology Innovations

Global Valuation of ISR Resources

- COI instance detected and reported by Blue yields a payoff proportional to the potential future damage avoided – the ***COI Instance Detection Value*** (CIDV)

- <u>Initial Theoretical Upper Bound</u> – With oracular knowledge about when and where each COI instance occurs and ability to perfectly detect and report instances as they occur, then all COI instances would be detected and reported and achieve the maximum possible CIDV

- <u>Tighter Theoretical Upper Bound</u> - Replacing oracular knowledge with a statistical model of COI occurrence while preserving perfect ability to detect and report all COI instances for a given period of surveillance yields the ***Unconstrained Expected ISR Value***

Constrained Expected ISR Value

- Constrained ISR system - imperfect detection and reporting with limited assets - seeks to maximize the **Constrained Expected ISR Value** (*CEPV*)

- Region of interest is partitioned into a set of **surveillance zones** (*sz*)

- Assigning an admissible configuration (*ac)* to a *sz* for a given interval of time yields an **Expected Assignment Value** (*EAV$_{ac,sz}$*), that, per COI instance, is the product of:
  – Payoff value of detecting the COI instance in that *sz*
  – Probability of occurrence of the COI instance in that *sz* during the time interval
  – Probability of detecting and reporting COI instance in that *sz* by the *ac*

- A **Collection Plan** *(CP)* is a feasible set of pairings (*ac,sz*)

Maximizing Collection Plan Value

- Objective is to maximize *CEPV*: the sum of $EAV_{ac,sz}$ for all (ac,sz) pairs obtained from specifying the collection plan:

$$\text{Max} \quad CEPV = \sum_{sz}\sum_{ac} EAV_{ac,sz} Assign_{ac,sz}$$

- Feasible collection plan requires specifying for the set of (ac, sz) pairings:
  - Allocation of ISR components (co) to admissible configurations (ac)
    - Number of ISR components is usually much smaller than the number of zones to surveille
  - Assignment of admissible configurations (ac) to surveillance zones (sz) respecting
    - Limit of at most one *ac* per *sz* (note an ac can have multiple sensors in one sz)
    - Some *ac* may cover more than one *sz* subject to some upper bound
    - Other constraints, such as allocations across FOBs

- First formulation - binary integer program solved with COTS code (CPLEX)

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

→ - Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept
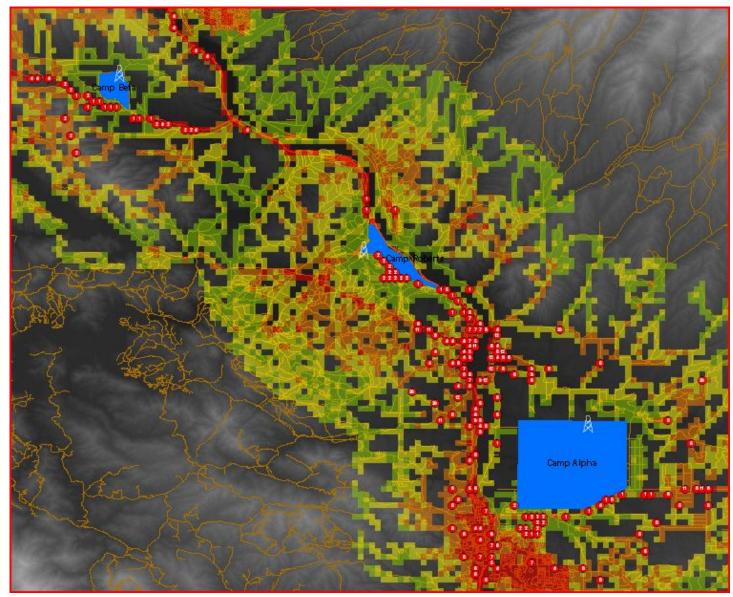
- VIR Technology Innovations

Optimization

- Solved assignment problem with
  - 14 kinds of ISR assets
  - 29 different admissible configurations (some may be unavailable based on number of ISR assets available)
  - 6178 surveillance zones in 3 FOB Operating Regions
  - MIP size: 222,000 variables, 179,000 constraints

- Problem formulated in MPL and solved in CPLEX
  - Total solution time on standard laptop is < 30 seconds
  - 15 - 20 seconds to load data from Excel/Text files into MPL
  - < 10 seconds for CPLEX to solve
  - Additional time (~ 1 minute) for MPL to write the solution back to Excel

Optimization Results

VPR Solver Time vs Pixelization for 3 FOBs
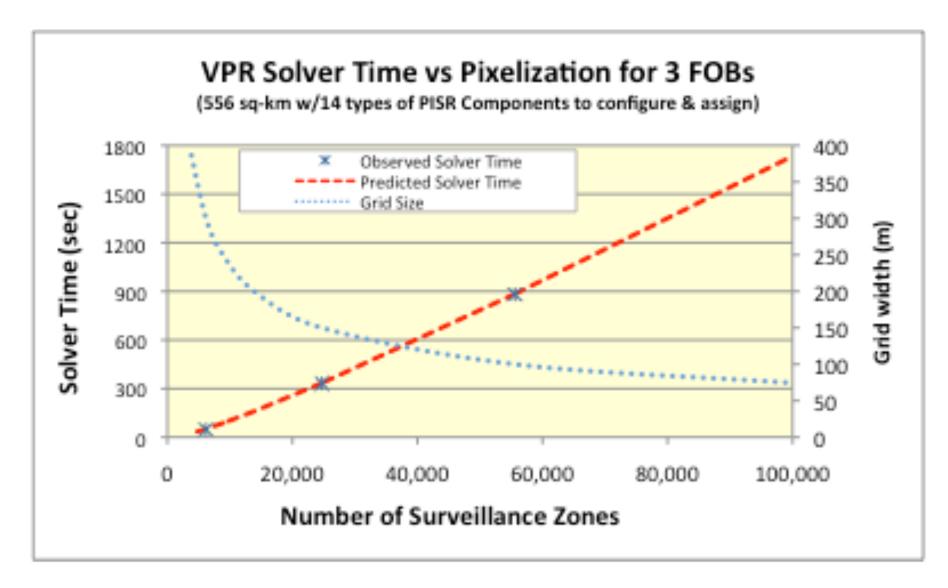(556 sq-km w/14 types of PISR Components to configure & assign)
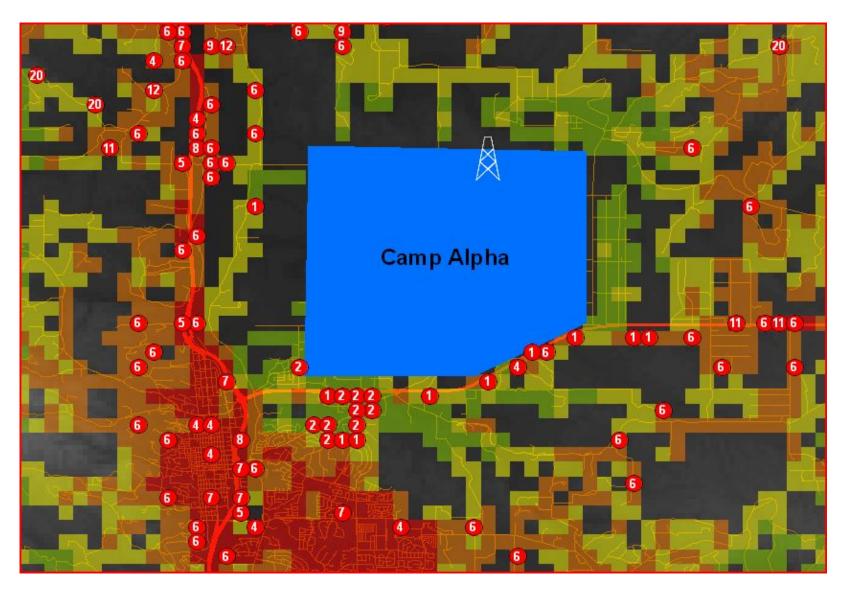
VIR Value Added

- **Objective** - measure the value of VIR assignment of ISR assets relative to current assignment processes

- **Ideal experiment** – compare VIR to actual human-managed ISR asset assignments

- **Achievable experiment** – develop a heuristic process that reasonably simulates a human-managed ISR assignment process

Heuristic Approach

- Three-stage process to simulate human approach

    - **Allocate components to FOBs**: allocate first/most components to largest (most Blue activity) FOBORs

    - **Assemble components into ACs**: maximize number of SZs that resulting ACs can surveil (break ties among ACs by highest probability of detecting IED emplacement)

    - **Assign ACs to SZs**: select SZs with highest X% probability of threat (TSP)

        - Assume assignment of ACs to a representative group of the selected SZs
        - Vary X to simulate ability of human to identify top-TSP SZs

Applied Heuristic Approach

- Apply heuristic to a group of 12 FOBORs
  - 4 large, 4 medium-sized, and 4 small

- Use an arbitrarily-selected set of components

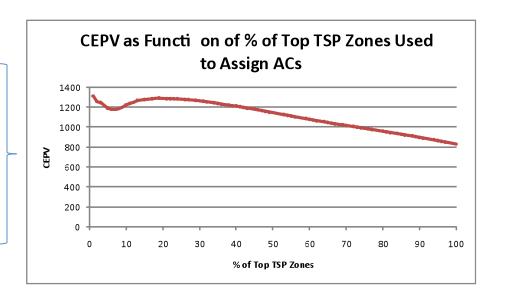| Description	# of each component
GBOSS	6
GBOSS Lite	8
Shadow/LEAP	5
MSIDS	8
UGSS	120
IRID II	10
Night Imager	24
MASF	10
ADDT	6
AECT	4
Comm	240
Radio Repeater	50
Video Scout	50
SMSS	12
User	Unlimited

- Compare resulting CEPV to VIR-optimized CEPV

VIR vs. Heuristic: Results

Scenario	Constrained Expected ISR Value (CEPV)
VIR - optimized	5723
Heuristic – Top 1% of SZs by TSP	1312
Heuristic – Top 10% of SZs by TSP	1225
Heuristic – Top 100% of SZs by TSP	830

CEPV as Functi on of % of Top TSP Zones Used to Assign ACs

VIR performs 4- 7 times as well as Heuristic Approach

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

→ - What-If Acquisition Analysis

- VIR System Concept

- VIR Technology Innovations

Cost-Constrained VIR

- Add to the baseline VIR optimization formulation
  - Component cost
  - Budget
  - Component usage variables
  - A budgetary resource constraint

- Intent to explore VIR's utility as a tool for supporting ISR portfolio optimization

- Within the context of this particular scenario what is the optimal mix of ISR components for a given level of investment?
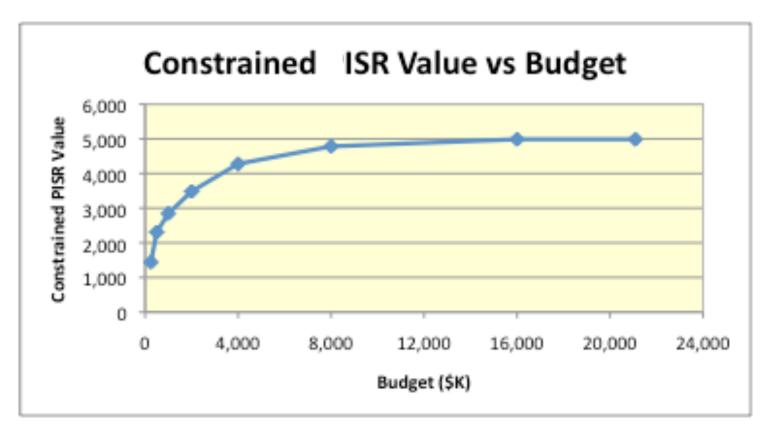
Adding Cost to Optimization

Name	ID	Cost ($K)	Baseline Qty	Total Cost ($K)	
GBOSS	C1	$ 1,000	3	$ 3,000	
GBOSS Lite	C2	$ 500	3	$ 1,500	
Shadow/LEAP	C3	$ 2,000	3	$ 6,000	
MSIDS	C4	$ 10	6	$ 60	
UGSS	C5	$ 5	60	$ 300	
IRID II	C6	$ 25	12	$ 300	
Night Imager	C7	$ 40	15	$ 600	
MASF	C8	$ 80	9	$ 720	
ADDT	C9	$ 100	6	$ 600	
AECT	C10	$ 100	0	$ -	*Note has 0.00 Pd against IED
Comm	C11	$ 1	90	$ 90	
Radio Repeater	C12	$ 1	4	$ 4	
Video Scout	C13	$ 10	30	$ 300	
SMSS	C14	$ 20	3	$ 60	
				$ 13,534	

- The model was given upper quantities of each type of ISR asset

- The amount of Constrained ISR Value to be extracted maximizes at a budget level of $13,534,000

- What happens to Constrained ISR Value as the budget is decremented? How does the optimal mix change?

Diminishing Returns
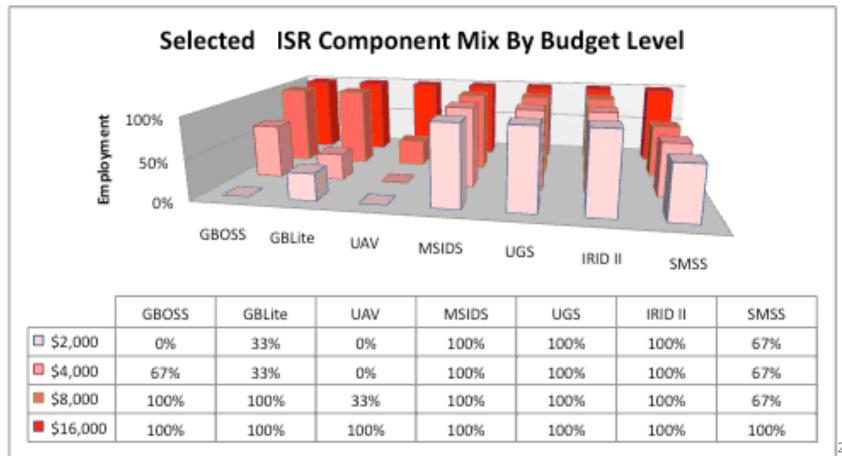

Constrained ISR Value vs Budget

- Shows how the value extracted from the 3 FOB region varied by budget level.
- Consistent with economic theory, the portfolio demonstrates diminishing returns
- How did the mix of assets change with the budget?

Portfolio Analysis

- Display focuses on 7 types of components.
- At small budgets, the GBOSS, GBLite, and UAV were not affordable relative to their value

Selected ISR Component Mix By Budget Level

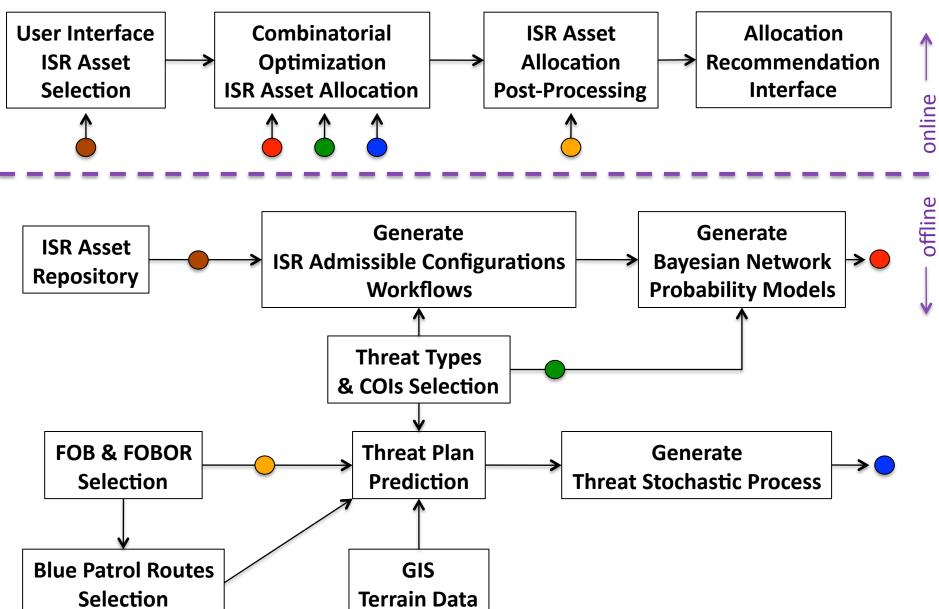|	GBOSS	GBLite	UAV	MSIDS	UGS	IRID II	SMSS
☐ $2,000	0%	33%	0%	100%	100%	100%	67%
☐ $4,000	67%	33%	0%	100%	100%	100%	67%
☐ $8,000	100%	100%	33%	100%	100%	100%	67%
☐ $16,000	100%	100%	100%	100%	100%	100%	100%

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

→ - VIR System Concept

- VIR Technology Innovations

VIR System Concept

Topics

- Objectives

- COIs, ISR Assets and Admissible Configurations (ACs)

- Continuous IPB: the Threat Stochastic Process (TSP)

- Maximizing Collection Plan Value

- Optimization Implementation

- What-If Acquisition Analysis

- VIR System Concept

→ - VIR Technology Innovations

VIR Technology Innovations

- Control-theoretic formulation of ISR Asset allocation
  - Gap between global value measurement of unconstrained and constrained ISR asset allocation

- Concept of admissible configuration of ISR assets
  - Admissibility defined as having workflow responsive to prosecution of COIs

- Mapping of ISR configuration workflows to Bayesian network probability models
  - Used to estimate probability of effectiveness of terrain situated ISR configurations

- Development of Threat Stochastic Process (TSP) providing mathematical infrastructure for continuous IPB
  - Integrates suitability of terrain to Red objectives, history of Red activities, support of local population to Red objectives, likelihood of Blue presence, effect of terrain on ISR asset effectiveness