Quantifying "Persistence" in the Context of Find-Fix-Finish (FFF)

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Introduction

Many in the Department of Defense have concluded that we need "persistent ISR" (Intelligence, Surveillance, and Reconnaissance):

*"Maintaining **persistent ISR** around the globe would allow the military to continue to function as a 'strategically relevant, continental United States-based projection force,' Bair said during the Defense News Media Group conference, ISR Integration 2003: The Net-Centric Vision, in Arlington, Va."*[1] — **Edward Bair** is the Army program executive officer for intelligence, electronic warfare and sensors.

*"We were trying to craft more of a story and a message that says we're moving away from, say, the reconnaissance paradigm to that **persistent surveillance** paradigm and let's look at what we're buying and see if that really does accomplish where we're trying to go."* [2] — **Kevin Meiners**; the director of intelligence strategies, technologies and assessments, Office of the Deputy Under Secretary of Defense for Intelligence and Warfighting Support.

*"We need long-term investment in **persistent ISR** capability with assured electromagnetic spectrum access utilizing up-to-date collection technologies to **find, track and interdict** mobile and technologically competent terrorist groups and platforms operating with the vast regions of Africa and Europe, including both air and maritime environments."* [3] — General **James L. Jones**, USMC, Commander United States European Command, before the House Armed Services Committee on 8 March 2006.

*"Precision operations are intelligence-driven. As noted above, we need to rebalance our **'find, fix, finish'** targeting cycle."* [4] — General **John P. Abizaid**, USA, Commander, United States Central Command, before the House Armed Service Committee on 15 March 2006.

In a 10 August 2006, interview in Secretary **Rumsfeld**'s office, the Secretary said, *"I was asked that when I was up at the confirmation hearings in January of '01, and I said intelligence. And if you think about this department, we have just enormous capability to **finish**. If you use the phrase "**find, fix and finish**," we can **finish** something if we can **find** it and **fix it in time** and location. The problem is **finding** it. And you can find big armies and big navies and big air forces, and we've gotten quite good at that in this department. It is a whale of a lot harder to deal with a network, with individuals, with people that don't wear uniforms, with people that mix among civilians and hide among innocent people."* [5]

And, finally, in a news briefing on 12 January 2006 with Secretary Rumsfeld and Chairman General **Peter Pace**, Secretary Rumsfeld said, *"And the reality that this department has responsibilities **to find and to fix and to finish** — to use the phrase — in terms of dealing with threats and enemies to this country, and a recognition that we have a great deal of ability to fix and — correction, to **finish** — in an operation and much less ability to **find** and **fix**, and the importance of seeing that our department over time recognizes that imbalance and does everything humanly possible to see that we find ways to link — we are the biggest user of intelligence — this department is — and we need to see that there is an intimate relationship in proximity and time between intelligence and operations."* [6]

These are just some of the quotes we see almost daily in Defense news publications, press conferences, testimonies to Congress, and briefings. The concept of "persistence" is a powerful enabler in ongoing operations, particularly in the context of a series of events often described as the "*kill chain*"; that is "*find-fix-finish*" (FFF). This indicates that we must first "find" (detect, acquire, and verify) our targets, then we must "fix" (track, obtain accurate locations and disseminate this information) the targets, then "finish" (engage and deliver the effects required by the concept of operations or rules of engagement) the targets. We acknowledge that there are other reasons, beyond FFF, for having persistent ISR capability, but, in this effort, we only focus on ISR in the context of FFF.

FFF, being a series of events or tasks, can be further decomposed into more detailed subordinate tasks. The Air Force, for years, has used F2T2EA (find-fix-track-target-engage-assess) as a more detailed kill chain. This paper will focus on FFF, with the understanding that the mathematics could be extended to accommodate finer resolution.

As an example, we analysts are often asked to determine if we should invest in a new ISR capability or in a new hypersonic munition. More capable ISR assets will improve our ability to "find" targets; but, hypersonic munitions will allow us to "finish" targets much more quickly. So, we need an analytic construct to examine these trade spaces.

Purpose

"Persistence" is a powerful concept but, without quantification, it becomes just another in an infinite parade of buzz words that permeate our military lexicon. The purpose of this article is to quantify persistence and use it to analyze various trade-spaces (systems, tactics, operations, costs) in terms of their impact on the kill chain FFF.

We will first derive an equation for the probability of accomplishing the kill chain - $P_{FFF}(T)$. Then, we will quantify the drivers of this probability. Next, we will develop a "persistence ratio" to quantify the relative impacts of persistent ISR. And, finally, we will show some results and insights.

(See **FFF,** *p. 12)*

Problem Setup and Solution

Usually, one discusses $P_{FFF}(T)$ as a set of conditional probabilities:

P[finish | fix] * P[fix|find] * P[find].

This is a valid approach as long as we know the specific time windows for the individual event probabilities. But, this is hardly ever the case. Most often we are faced with a given time window, or window of target opportunity, in which the entire FFF process must take place. For example, our window of target opportunity may be from the time a terrorist drives up in front and enters a restaurant until the time he departs the restaurant. We must find, fix, and finish in that time window.

Graphically, this time window, *T*, is shown in Figure 1 along with the individual FFF event times.

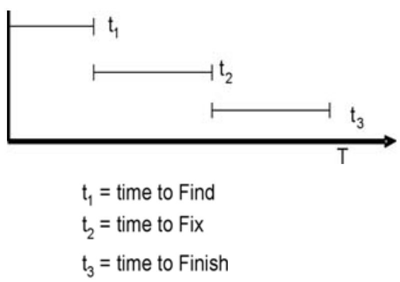

Figure 1. Time Window, *T*, and times to "find", "fix", "finish"

Once we find, we can fix, and once we fix, we can finish. So, instead of conditional probabilities with known times for each event "F", we want to solve for the probability of accomplishing all "Fs" in the window of opportunity, which is

$$P_{FFF}(T) = P[(t_1 \le T) \cap (t_2 \le T - t_1) \cap (t_3 \le T - t_1 - t_2)] \quad (1)$$

From Koopman,[7] we know that "when the looking is done continuously during a time *t* under unchanging conditions, the probability *p(t)* of detection is given by"

$$p(t) = 1 - e^{-\lambda t} \quad (2)$$

where ? is the rate of "detection." Since this is a cumulative probability, the time between detections follows the exponential density function

$$f(t) = \lambda e^{-\lambda t} \quad (3)$$

What Koopman describes is formalized by Ross,[8] in that these assumptions of a counting process and of stationary independent increments ("the distribution of the number of events that occur in any interval of time depends only on the length of the time interval") make these Poisson Processes which have been used extensively in stochastic modeling.

We will extend this beyond detection and make the assumption that this is representative of each of the three events (find-fix-finish). While we have traditionally modeled the probability of damage given attacks, this approach incorporates the probability of "finish" within a time interval. In our approach, the emphasis on time is much more appropriate for the mobile targets, which require "finding and fixing", since these targets are very vulnerable to strikes once located. The modeling time for "finish" events following an exponential distribution is very reasonable for cases where strike assets are loitering to flex on targets of opportunity as they appear dispersed across a region. We are also assuming that "find and fix" means that we are keeping the target on "track" or that we don't break track.

We consider that the λ_is encompass all the spatial aspects of target density, revisits, and geography so that we can address all these issues in the temporal domain. So, allowing that the λ_is for each of the events ("Fs") may not be equal (it's unlikely they would be equal and that solution is trivial), the solution to equation (1) becomes

$$P_{FFF}(T) = P[(t_1 \le T) \cap (t_2 \le T - t_1) \cap (t_3 \le T - t_1 - t_2)] =$$

$$\int_0^T \lambda_1 e^{-\lambda_1 t_1} \int_0^{T-t_1} \lambda_2 e^{-\lambda_2 t_2} \int_0^{T-t_1-t_2} \lambda_3 e^{-\lambda_3 t_3} \, dt_3 \, dt_2 \, dt_1 \quad (4)$$

After integrating the right hand side of equation (4) we get

$$P_{FFF}(T) = 1 - e^{-\lambda_1 T}\left(\frac{\lambda_2 \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)}\right) - e^{-\lambda_2 T}\left(\frac{\lambda_1 \lambda_3}{(\lambda_2 - \lambda_1)(\lambda_2 - \lambda_3)}\right) - e^{-\lambda_3 T}\left(\frac{\lambda_1 \lambda_2}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)}\right) \quad (5)$$

A general expression for this $P_{FFF}(T)$ is

$$P_{FFF}(T) = 1 - \sum_j \frac{\left[e^{-\lambda_j T} * \left(\prod_{i \ne j} \lambda_i \right) \right]}{\prod_{i \ne j} (\lambda_j - \lambda_i)} \quad (6)$$

If we now let $\theta_i = 1/\lambda_i$ be the mean-time-to event *i*, we can rewrite equation (5) as

$$P_{FFF}(T) =$$

$$1 - e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1^2}{(\theta_1 - \theta_2)(\theta_1 - \theta_3)}\right) - e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2^2}{(\theta_2 - \theta_1)(\theta_2 - \theta_3)}\right) - e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3^2}{(\theta_3 - \theta_1)(\theta_3 - \theta_2)}\right) \quad (7)$$

A general expression for this $P_{FFF}(T)$ is

$$P_{FFF}(T) = 1 - \sum_j \frac{\left[e^{-T/\theta_j} * \theta_j^2 \right]}{\prod_{i \ne j} (\theta_j - \theta_i)} \quad (8)$$

Limits

We can readily see that this probability of finding-fixing-finishing in a time window *T* is a function of the length of *T* and the times to accomplish the individual events, θ_1, θ_2, θ_3. Also, we note the limits of equation (7) when each of the θ_is goes to 0 (i.e., instantaneous event).

$\theta_1 \to 0$

$$P = 1 - e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2}{\theta_2 - \theta_3}\right) - e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3}{\theta_3 - \theta_2}\right)$$

$\theta_2 \to 0$

$$P = 1 - e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1}{\theta_1 - \theta_3}\right) - e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3}{\theta_3 - \theta_1}\right)$$

$\theta_3 \to 0$

$$P = 1 - e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1}{\theta_1 - \theta_2}\right) - e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2}{\theta_2 - \theta_1}\right)$$

Impact of the θ_is

We can now determine how the θ_is impact the overall $P_{FFF}(T)$. We do this by taking the partial derivatives of equation (7) with respect to each of the θ_is. These quantify the *changes in the $P_{FFF}(T)$ given incremental changes in each θ_i*. These are calculated as

$$\frac{\partial P}{\partial \theta_1} =$$

$$-e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1^2}{(\theta_3 - \theta_1)^2(\theta_2 - \theta_1)} + \frac{\theta_1^2}{(\theta_2 - \theta_1)^2(\theta_3 - \theta_1)} + \frac{T}{(\theta_3 - \theta_1)(\theta_2 - \theta_1)} + \frac{2\theta_1}{(\theta_3 - \theta_1)(\theta_2 - \theta_1)}\right)$$

$$+ e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2^2}{(\theta_3 - \theta_2)(\theta_2 - \theta_1)^2}\right) - e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3^2}{(\theta_3 - \theta_2)(\theta_3 - \theta_1)^2}\right) \quad (9)$$

$$\frac{\partial P}{\partial \theta_2} =$$

$$e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2^2}{(\theta_3 - \theta_2)^2(\theta_2 - \theta_1)} - \frac{\theta_2^2}{(\theta_2 - \theta_1)^2(\theta_3 - \theta_2)} + \frac{T}{(\theta_3 - \theta_2)(\theta_2 - \theta_1)} + \frac{2\theta_2}{(\theta_3 - \theta_2)(\theta_2 - \theta_1)}\right)$$

$$+ e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1^2}{(\theta_3 - \theta_1)(\theta_2 - \theta_1)^2}\right) - e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3^2}{(\theta_3 - \theta_1)(\theta_3 - \theta_2)^2}\right) \quad (10)$$

$$\frac{\partial P}{\partial \theta_3} =$$

$$e^{-\frac{T}{\theta_3}}\left(\frac{\theta_3^2}{(\theta_3-\theta_2)^2(\theta_3-\theta_1)}+\frac{\theta_3^2}{(\theta_3-\theta_1)^2(\theta_3-\theta_2)}-\right.$$

$$\left.\frac{T}{(\theta_3-\theta_1)(\theta_3-\theta_2)}-\frac{2\theta_3}{(\theta_3-\theta_1)(\theta_3-\theta_2)}\right)$$

$$+e^{-\frac{T}{\theta_1}}\left(\frac{\theta_1^2}{(\theta_2-\theta_1)(\theta_3-\theta_1)^2}\right)-e^{-\frac{T}{\theta_2}}\left(\frac{\theta_2^2}{(\theta_2-\theta_1)(\theta_3-\theta_2)^2}\right) \quad (11)$$

Some example values of equations (9), (10), and (11) are shown in Table 1. These partial derivatives can now be used to develop a metric for "persistence."

T	$\partial P/\partial \theta_1$	$\partial P/\partial \theta_2$	$\partial P/\partial \theta_3$
10	-0.01117	-0.00709	-0.00516
20	-0.02409	-0.01887	-0.01509
30	-0.02343	-0.02198	-0.01941
40	-0.01700	-0.01854	-0.01811
50	-0.01072	-0.01324	-0.01431
60	-0.00627	-0.00855	-0.01022
70	-0.00350	-0.00518	-0.00684
80	-0.00190	-0.00300	-0.00437
90	-0.00102	-0.00168	-0.00270
100	-0.00054	-0.00093	-0.00163

Table 1. Partial Derivatives as a Function of *T* (minutes): θ_1 = 5 minutes, θ_2 = 10 minutes, θ_3 = 15 minutes

Notice that Table 1 shows negative values for the partial derivatives, since increases (decreases) in the θ_is would mean a decrease (increase) in $P_{FFF}(T)$.

With some manipulations on equations (9), (10), and (11), it is interesting to note that we can swap θ_i for θ_j and the "swapped" partials are equal to the original partials, the unchanged partial remains the same, and $P_{FFF}(T)$ also remains the same. In fact, if we swap all three θs, then all the "swapped" partials are equal to the original partials and $P_{FFF}(T)$ still remains the same. For example, let θ_1 =10, θ_2 =15, θ_3 =50, and T = 60. Then,

$$P_{FFF}(T) = 0.4845$$
$$\frac{\partial P}{\partial \theta_1} = -0.010007$$
$$\frac{\partial P}{\partial \theta_2} = -0.009737$$
$$\frac{\partial P}{\partial \theta_3} = -0.006251$$

If we swap the θs to be θ_1 =50, θ_2 =10, θ_3 =15, and keep T = 60, we get

$$P_{FFF}(T) = 0.4845$$
$$\frac{\partial P}{\partial \theta_1} = -0.006251$$
$$\frac{\partial P}{\partial \theta_2} = -0.010007$$
$$\frac{\partial P}{\partial \theta_3} = -0.009737$$

Persistence Ratio

Here, we focus on ISR as the prime driver for the "find" event. Although persistence can be thought of in the context of any of the three events, we will now focus on the "find" event to develop a Persistent ISR Ratio (PIR). We can obtain a measure of the rate of change in $P_{FFF}(T)$ for "find" relative to each of the other two F's. This PIR is calculated as

$$\text{PIR} = \min\left\{ \frac{\partial P/\partial\theta_1}{\partial P/\partial\theta_2}\ ,\ \frac{\partial P/\partial\theta_1}{\partial P/\partial\theta_3} \right\} \quad (12)$$

If PIR >1, then reductions (improvements) in θ_1 result in larger increases in $P_{FFF}(T)$ compared to equivalent reduction of either θ_2 or θ_3. If PIR <1, then small reductions in either θ_2 or θ_3 would result in larger increases in $P_{FFF}(T)$ than would reductions in q_1.

Example #1

Let's look at an example with our time window T going from 10 minutes to 190 minutes while θ_1 = 20 minutes, θ_2 = 30 minutes, and θ_3 = 40 minutes. Figure 2 shows the effect on $P_{FFF}(T)$ (Equation (7)) of shrinking or expanding the time window T.

We also are interested in the partial derivatives from equations (9), (10), and (11) and how they vary over T. This is shown in Figure 3. Since the partial derivatives are negative, we have multiplied them by -1 and plotted them as positive values for visual purposes.

This graph gives an interesting insight. When the time window T is fairly long (e.g., 150 minutes), $\partial P/\partial \theta_3$ is the most negative of the partial derivatives and we get more benefit ($P_{FFF}(T)$ increases more rapidly) by reducing θ_3, the time it takes to "fin-

(See **FFF,** *p. 14)*

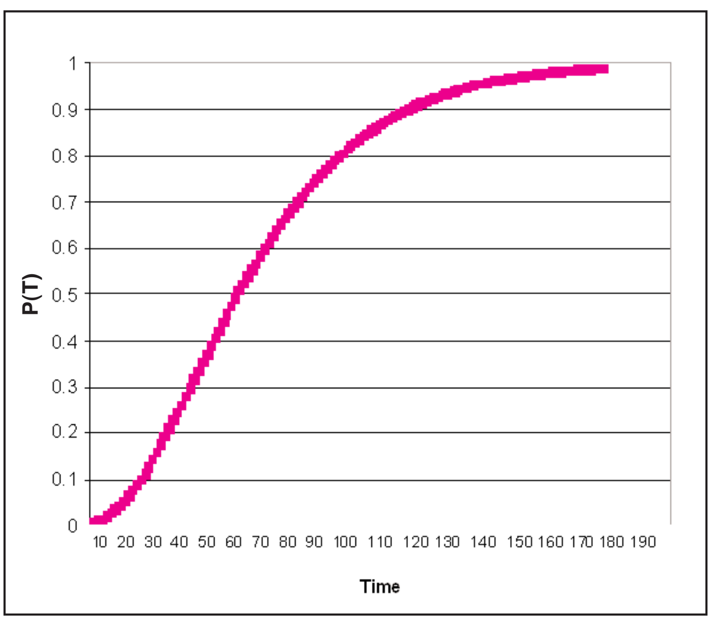

Figure 2. $P_{FFF}(T)$ as a Function of *T*.

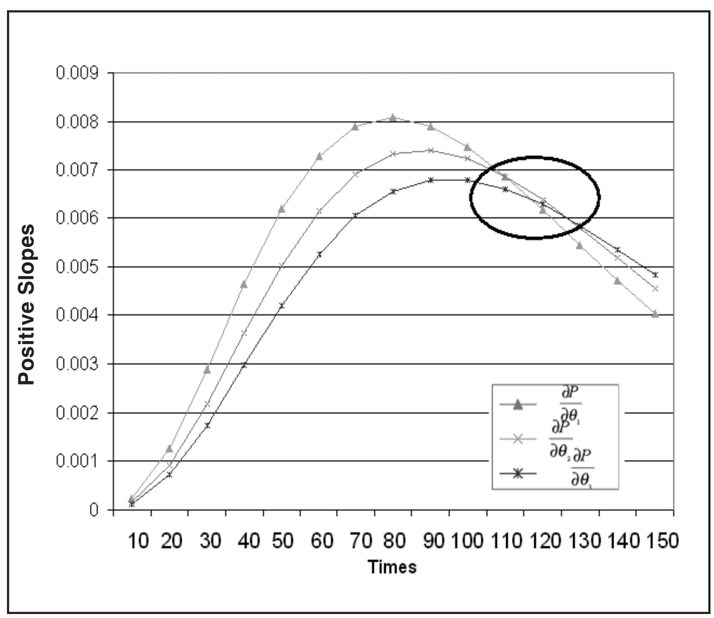

Figure 3. Positive Partial Derivatives as a Function of *T*.

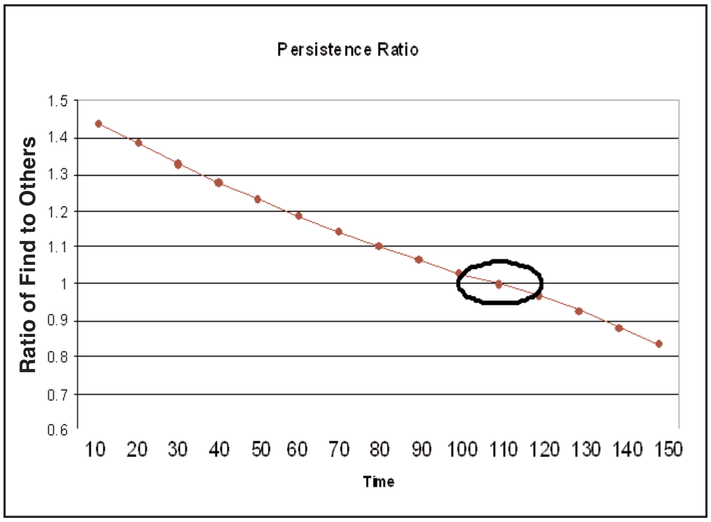

Figure 4. PIR as a Function of *T*.

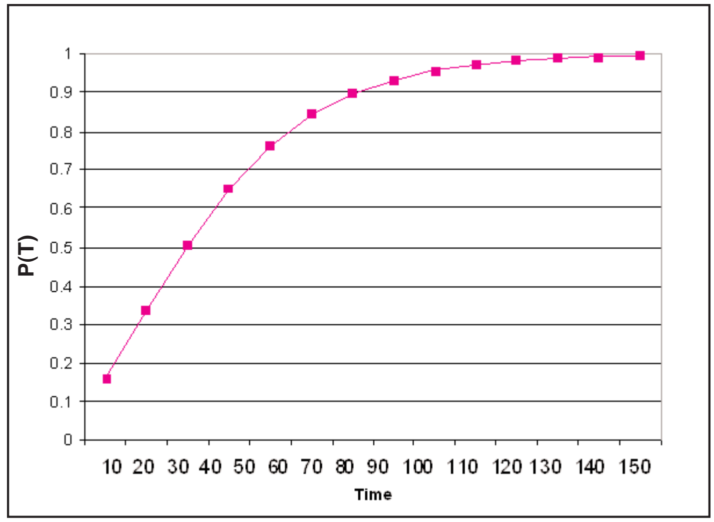

Figure 5. P_{FFF}(T) as a Function of *T*.

ish" the target (i.e., reduce the largest θ_i). But, at some point (i.e., 110 minutes), $\partial P/\partial\theta_1$ becomes the most negative and it is more advantageous to decrease θ_1 to get the largest improvement in P_{FFF}(T). This can be seen in Figure 4, where we plot the PIR as a function of *T*.

Figure 4 clearly shows that PIR>1 up to 110 minutes and is less than 1 for a time window greater than 110 minutes.

Example #2

Now, let's look at an example with our time window *T* going from 10 minutes to 150 minutes while θ_1 = 20 minutes, θ_2 = 15 minutes, and θ_3 = 10 minutes. Figure 5 shows the effect on P_{FFF}(T) (Equation (7)) of shrinking or expanding the time window *T*.

Again, we plot the positive partial derivatives from equations (9), (10), and (11) and how they vary over *T*. This is shown in Figure 6.

This graph confirms the previous interesting insight with a little twist. When the time window, *T*, is fairly long, $\partial P/\partial\theta_1$ is the most negative partial derivative and we get more benefit (P_{FFF}(T) increases more rapidly) from reducing θ_1 the time it takes to "find" the target (i.e., reduce the largest θ_i). But, at some point (i.e., between 60 and 70 minutes), $\partial P/\partial\theta_2$ becomes the most negative and it is more advantageous to decrease θ_2 (improve the time to "find") to get the largest improvement in P_{FFF}(T). Then, at 50 minutes, $\partial P/\partial\theta_3$ becomes the most negative and it is more advantageous to decrease θ_3 (improve the time to "finish") to get the largest improvement in P_{FFF}(T). This can be seen in Figure 7 where we plot the PIR as a function of *T*.

Figure 7 clearly shows that PIR>1 beyond 70 minutes.

The startling insight is that at large values of *T*, reducing the **largest** θ_i yields the largest increase in P_{FFF}(T). But, as *T* gets smaller, reducing the **smallest** θ_i yields the largest increase in P_{FFF}(T). It all depends on the values of *T* and the θ_is.

Solving for the Window of Opportunity:

Figure 6 shows that as the total time to strike a target increases, the impact of increases in the response rates becomes insignificant. In equations (2) and (3), we developed each phase of the kill chain as a Poisson Process and the entire kill chain as a sequence of Poisson Process. So, based on threat projections of the rate of targets of opportunities, we can determine the total time necessary to achieve a desired success rate. Thus, this model can set the goal for overall capability and evaluate component improvements to achieving that goal.

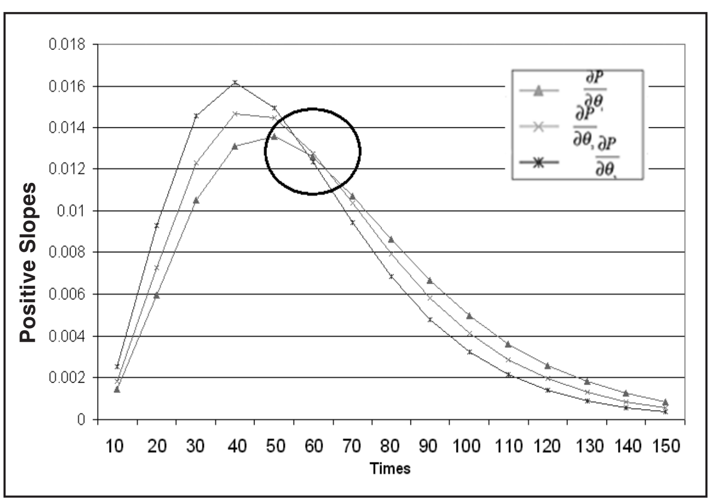

Figure 6. Positive Partial Derivatives as a function of *T*.

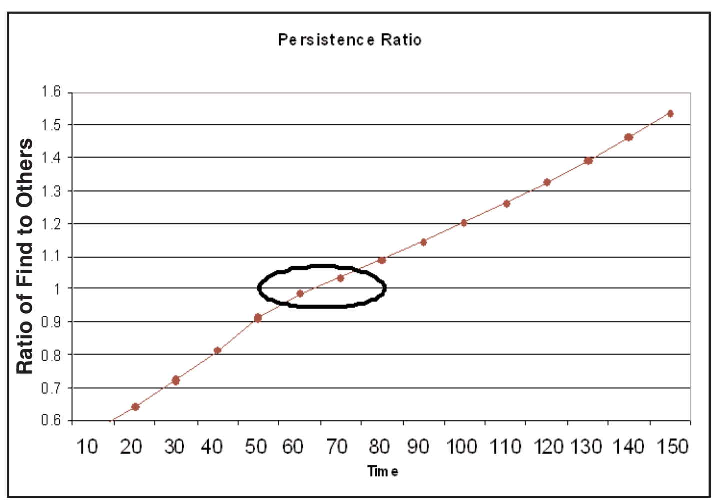

Figure 7. PIR as a function of *T*.

To illustrate this application, let's say we want to find the minimum window of opportunity given a set of θ_is. That is, if we know our θ_is and we want no less than a given $P_{FFF}(T)$, we can solve equation (7) for *T*. For example, if $\theta_1 = 10$ minutes, $\theta_2 = 15$ minutes, and $\theta_3 = 5$ minutes and we want no less than a $P_{FFF}(T) = 0.80$, we solve equation (7) for *T* which yields $T = 43.19$ minutes. This tells us that, given these θ_is, if we have a window of opportunity equal to or greater than 43.19 minutes, we have a $P_{FFF}(T) > 0.80$.

Operational Considerations:

By focusing on only the temporal aspect, we have not totally addressed the issue that persistence is especially critical for sensor phenomena where we are dependent on the target creating an observable, e.g., movement in the case of MTI or videoing a door for a terrorist to exit. Persistence provides the opportunity for high target update rates that give a better idea of target intent and, hence, make the front-end decision to even enter the FFF cycle.

Next step:

The next step is to obviously incorporate costs so that one can perform cost-benefit trade studies for making improvements in each of the "Fs". ***It is clear that it is not always the best action to improve "find" if one wants to improve the overall kill chain! It depends on the times to "fix" and "finish" and the window of opportunity.***

Conclusions:

We have developed a Persistent ISR Ratio (PIR) that can be used to determine whether improvements in "finding" targets actually gives us the best improvement in the kill chain – $P_{FFF}(T)$. It measures *persistent ISR* relative to the other two Fs – "fix" and "finish."

We can use this aggregated set of calculations to get ROMs on effectiveness and cost-benefit trades for systems and CONOPS in their impact on improving the kill chain. So, to determine if we should invest in a new ISR capability or in a new hypersonic munition…let's look at the trade space.

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Biography

*Dr **Roy Rice** began his Air Force career following graduation from the Air Force Academy with a B.S. in Mathematics, later earning an M.S. in Operations Research from the Air Force Institute of Technology and a PhD in Operations Research from the University of Texas. His military service includes tours as Deputy Director for the Office of Aerospace Studies, Force Structure Analyst for the Joint Staff and tours at the Air Force Logistics Management Agency, the Air Force Operational Test and Evaluation Center, and the Oklahoma Air Logistics Center. During his Air Force career, Dr Rice developed innovative methodologies and tools and led assessments that have addressed a wide range of defense problems such as optimizing performance and costs of C4ISR forces mixes, cost and operational performance trade studies; strategic force optimization and strategic stability; logistics analyses; and strategic modernization. Dr Rice is a MORS Fellow, a Past President of the Society, recipient of the Vance R. Wanner Award and a licensed Professional Engineer. He currently serves as Chief Scientist at Teledyne Brown Engineering where he is responsible for identifying and developing analysis, modeling, and simulation methodologies and tools.* ✪

CHALLENGES

(continued from p. 10)

against which we evaluate our systems. In some cases recent fielding initiatives for Iraq and Afghanistan have shrunk a decade long process to a year or less. Our analysts performing research, development, and acquisition support and doctrine development have to be networked with the soldiers and analysts in the field so that the wartime environment and lessons learned are properly captured in our assessments.

6. **Stationing the Force to Meet the Emerging Strategic Demands While Providing Infrastructure and Services to Enable Mission Accomplishment**. Three decisions, all backed by strong independent analysis, have merged to create a severe stationing challenge: 1) the Army plans to grow in accordance with the decision announced by the President this past February; 2) the Base Realignment and Closure (BRAC) Act for 2005 mandates a re-arrangement of CONUS installations based on pre-growth estimates; and 3) our oversees basing is changing in-line with the Office of Secretary of Defense Global Basing and Posture Strategy which was done before the growth estimates, in parallel with BRAC, and before the prolonged engagement in Iraq was envisioned. All of these activities now need to be balanced and the analysis supporting each must be integrated.
7. **Transformation Business Practices to Better Enable Army Transformation**. The Army has embraced a broad set of management reforms and is drawing upon Lean Six Sigma education to enable efficiency improvements. As most of the OR community knows, Lean Six Sigma has its roots in operations research and industrial engineering. The leadership of the Army is now fully embracing using fact-based, quantitative methods for improving how the Army runs. We need to be open minded and responsive to help where we can.
8. **Obtain Full, Timely, and Predictable Funding to Sustain the Army's Global Commitments**. The last objective (and first in the Army Posture Statement) identifies a need to engage with Congress and the American people. Although not an analysis activity in itself, analysis sup-

(See **CHALLENGES**, *p. 16)*