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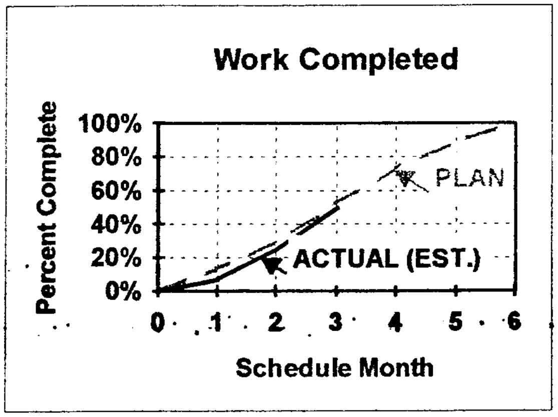
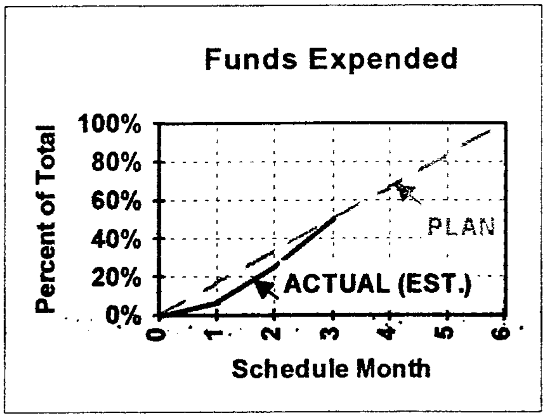
TECHNICAL PROGRESS REPORT #3

Contract No.:	N00014-95-C-0082
Contract Type:	Phase I SBIR
Contract Title:	A High-Resolution Unconventional Imager for Missile Defense Applications
CLIN:	0001AC
Submitted By:	Lumen Laboratories, Inc. (Cage Code: 01TU7)
Submitted To:	Dr. William Stachnik, ONR Program Officer (DoDAAD: N00014)
Date Submitted:	1 May 1995
Report Period:	**March 1995**

Work Completed To Date (Est.):	**52%**	**Funds Expended To Date (Est.):**	**50%**
Planned Work Completed To Date:	**52%**	**Planned Funds Expended To Date:**	**50%**





Summary of Technical Progress This Period

The program remains on schedule and budget. The major accomplishments for this reporting period are summarized below by Statement of Work (SOW) task.

Perform Top-Level Design Tradeoffs (SOW Item 1) ***AND***
Complete A Preliminary ASI Hardware Design (SOW Item 3)

The bulk of this report is dedicated to the two SOW tasks listed above because of the significance of the results obtained in these areas this reporting period.

During this reporting period a detailed MathCAD™-based ASI signal performance model was completed and checked. Also, the laser energy requirements were estimated for the three potential ASI military applications reported last period. The results were discouragingly high, ranging from 35 Joules to 135 Joules per pulse. (The laser pulses N times to collect an N x N pixel image.) This led to a careful analysis of tradeoffs affecting transmit energy requirements. A significant understanding resulted; the ASI imager works extremely well (from a laser energy point of view) when very small objects like missiles or space debris are imaged over large distances. Also, laser energy requirements decrease when the transmitter wavelength is increased. In each case the smallest speckle lobe increases in size, and more photons are collected as the subaperture size is scaled accordingly. Interestingly, this suggests that ASI can fill a very unique niche where radar cannot supply the spatial resolution and conventional optics are too bulky and expensive to perform long-range non-cooperative target identification of small targets. Hence ASI may be "the only game in town" as an adjunct sensor for Patriot missile batteries, as a non-cooperative target I.D. sensor on fighter aircraft protecting a Navy carrier group, or as a space debris imager protecting the space shuttle or space station.

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A detailed model of top-level ASI performance was constructed in MathCAD™, a computer-based symbolic mathematical analysis environment. This model accepts user inputs for the following parameters:

- maximum and minimum target size,
- target reflectance,
- maximum target range,
- atmospheric attenuation (1 way),
- background light level,
- transmitter pulse width,
- transmit line overfill factor at target (multiple of max. target width),
- desired target image resolution,
- laser wavelength,
- receiver spectral filter width,
- receiver optical transmission,
- receiver element (subaperture) field of view (solid angle),
- desired number of photons at the subaperture detector per pulse,
- subaperture length and width over-sampling factor (relative to Nyquist).

The model calculates a number of system parameter values such as:

- required transmitter pulse energy,
- number of background light photons integrated per measurement (noise),
- number of subapertures required,
- a single subaperture's light collection area,
- a single subaperture's length and width,
- the entire subaperture array's length and width,
- transmit aperture length and width,
- smallest speckle lobe's length and width.

This modeling tool was used to calculate system parameters to meet the requirements for the three potential military applications reported last period. Since last period some of the requirements for these applications were refined (see Table 1) based on discussions with various contractors familiar with the E2C program[1] and non-cooperative target identification.[2] Modeling result summaries are listed in Figures 1 through 3. The reader should note the high laser pulse energies required to fulfill the various mission requirements (35 - 139 Joules).

A primary driver for the high pulse energy requirements is atmospheric attenuation. The attenuation values listed in Table 1 were calculated using PC-Tran™, a software-based model. Curves of one-way attenuation versus target range are shown in Figures 4 through 6 for the E2C, non-cooperative target identification and stealth aircraft detection missions, respectively. The target reflectivity and background light levels used are based on values consistent with values measured in past laser radar programs managed by the principal investigator.[3]

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[1] Private discussions with Mr. Woolf Gross, Director, International Programs, Northrop Grumman International, Inc. Various information was drawn from "E2C Introduction and Systems Overview" supplied to Lumen Labs by Mr. Gross.

[2] Private discussions with Mr. Eden Mei, Member, Technical Staff, Northrop Electronic Systems Division, Hawthorne, CA. Mr. Mei is familiar with TCS and IRST electro-optical sensors currently used for non-cooperative target detection and identification on the F-14 platform.

[3] These programs include the U.S. Army's helicopter obstacle avoidance (OASYS) program, the DARPA-funded Active Ranging, Tracking and Signature Sensor (ARTS) Program, and smart munition fuze ladar work conducted for the Office of the Secretary of Defense.

Table 1. ASI Parameters for Three Potential Military Applications (Updated).

ASI Parameter	*E2C Tactical Surveillance Adjunct Sensor*	*Fighter Non-Cooperative Target I.D.*	*Low-Altitude Stealth Aircraft Detection*
Sensor Platform Altitude	6.1 km (20,000 ft.)	12.2 km (40,000 ft.)	0 km (Sea Level)
Worst-Case Viewing Slant ∠	- 40°	- 30°	± 15° from zenith
Max. Target Range	300 km (162 naut. mi.)	150 km (81 naut. mi.)	2 km (6,500 ft.)
1-Way Atmos. Attenuation	0.2	0.2	0.7
Background Level	100 W/m^2-µm-sr	100 W/m^2-µm-sr	300 W/m^2-µm-sr
Desired Resolution at Target	30 cm (12")	20 cm (8")	10 cm (4")
Laser Wavelength	1.06 µm	1.06 µm	1.06 µm
Max. Target Width	30 m	20 m	30 m
Min. Target Width	2 m	1 m	2 m
Target Reflectivity	10%	10%	3%
Number of Subapertures	200	200	600
Subap. Array Length, Width	1.0 m x 0.5 m	0.8 m x 0.4 m	21 mm x 11mm
Transmit Aperture Length, Width	1.0 m x 5 mm	0.8 m x 4 mm	21 mm x <1 mm
Required Pulse Energy (Calc.)	**139 Joules**	**61 Joules**	**35 Joules**

ASI SPECKLE IMAGER SIGNAL STRENGTH MODEL SUMMARY

E2C Scenario

User Inputs (in mks)...

Target

$MaxTargSiz = 30$

$MinTargSiz = 2$

$TargRefl = 0.1$

$Range = 3\cdot 10^{5}$

Atmos & Bgrnd

$Atten1Way = 0.2$

$Background = 100$

Transmit

$PulseWidth = 1\cdot 10^{-8}$

$TransmitFloodFactor = 2$

System

$ImgResol = 0.3$

$Wavelength = 1.06\cdot 10^{-6}$

Receiver

$SpectralWidth = 1\cdot 10^{-8}$

$RecOpticalTrans = 0.6$

$\Omega\ sub = 7.615\cdot 10^{-5}$

$PrimePhotCnt = 590$

$SubapLengthFactor = 1$

$SubapWidthFillFact = 1$

Intermediate Derived Values ....

$TransApLength = 1.06$

$MinSpeckleLength = 1.06$

$SubapLength = 0.53$

$SubapArrayLength = 0.53$

$SubapArea = 0.003$

$TransApWidth = 0.005$

$MinSpeckleWidth = 0.011$

$SubapWidth = 0.005$

$SubapArrayWidth = 1.06$

$NumPixelsReqd = 200$

Calculate Required Transmitter Pulse Energy, Et ...

$$Et := \frac{Np\cdot h\cdot \nu\cdot \pi\cdot R^{2}}{\rho\cdot \tau\ atm^{2}\cdot \tau\ opt\cdot Fbeamfill\cdot Asub}$$

$Et = 138.663$

Calculate Number of Background Photons, Nb (Assume polarization rejection factor of 2X)

$$Nb := \frac{Bg\cdot Asub\cdot \delta\lambda\cdot \Omega\ sub\cdot \tau\ opt\cdot \Delta t}{2\cdot (h\cdot \nu)}$$

$Nb = 3.436\cdot 10^{3}$ $\sqrt{Nb} = 58.614$

Figure 1. Summary of Modeling Results for E2C Adjunct Surveillance Sensor.

ASI SPECKLE IMAGER SIGNAL STRENGTH MODEL SUMMARY

Non-Coop. Target I.D. Scenario

User Inputs (in mks)...

Target

$MaxTargSiz = \underline{20}$

$MinTargSiz = \underline{1}$

$TargRefl = \underline{0.1}$

$Range = \underline{1.5 \cdot 10^{5}}$

Atmos & Bgrnd

$Atten1Way = \underline{0.2}$

$Background = \underline{100}$

Transmit

$PulseWidth = \underline{1 \cdot 10^{-8}}$

$TransmitFloodFactor = \underline{2}$

System

$ImgResol = \underline{0.2}$

$Wavelength = \underline{1.06 \cdot 10^{-6}}$

Receiver

$SpectralWidth = \underline{1 \cdot 10^{-8}}$

$RecOpticalTrans = \underline{0.6}$

$\Omega\ sub = \underline{7.615 \cdot 10^{-5}}$

$PrimePhotCnt = \underline{440}$

$SubapLengthFactor = \underline{1}$

$SubapWidthFillFact = \underline{1}$

Intermediate Derived Values ....

$TransApLength = \underline{0.795}$

$MinSpeckleLength = \underline{0.795}$

$SubapLength = \underline{0.397}$

$SubapArrayLength = \underline{0.397}$

$SubapArea = \underline{0.002}$

$TransApWidth = \underline{0.004}$

$MinSpeckleWidth = \underline{0.008}$

$SubapWidth = \underline{0.004}$

$SubapArrayWidth = \underline{0.795}$

$NumPixelsReqd = \underline{200}$

Calculate Required Transmitter Pulse Energy, Et ...

$$Et = \frac{Np \cdot h \cdot \nu \cdot \pi \cdot R^{2}}{\rho \cdot \tau_{atm}^{2} \cdot \tau_{opt} \cdot Fbeamfill \cdot Asub} \qquad Et = \underline{61.28}$$

Calculate Number of Background Photons, Nb (Assume polarization rejection factor of 2X)

$$Nb = \frac{Bg \cdot Asub \cdot \delta\lambda \cdot \Omega_{sub} \cdot \tau_{opt} \cdot \Delta t}{2 \cdot (h \cdot \nu)} \qquad Nb = \underline{1.933 \cdot 10^{3}} \qquad \sqrt{Nb} = \underline{43.961}$$

Figure 2. Summary of Modeling Results for Non-Cooperative Target I.D. Sensor.

ASI SPECKLE IMAGER SIGNAL STRENGTH MODEL SUMMARY

Stealth Aircraft Detection - Ground-Based "Fence"

User Inputs (in mks)...

Target
$MaxTargSiz = 30$
$MinTargSiz = 2$
$TargRefl = 0.03$
$Range = 2\cdot 10^{3}$

Atmos & Bgrnd
$Atten1Way = 0.7$
$Background = 300$

Transmit
$PulseWidth = 1\cdot 10^{-8}$
$TransmitFloodFactor = 33$

System
$ImgResol = 0.1$
$Wavelength = 1.06\cdot 10^{-6}$

Receiver
$SpectralWidth = 1\cdot 10^{-8}$
$RecOpticalTrans = 0.6$
$\Omega\ sub = 8.529\cdot 10^{-4}$
$PrimePhotCnt = 100$
$SubapLengthFactor = 1$
$SubapWidthFillFact = 1$

Intermediate Derived Values ....

$TransApLength = 0.021$
$MinSpeckleLength = 0.021$
$SubapLength = 0.011$
$SubapArrayLength = 0.011$
$SubapArea = 3.745\cdot 10^{-7}$
$TransApWidth = 2.141\cdot 10^{-6}$
$MinSpeckleWidth = 7.067\cdot 10^{-5}$
$SubapWidth = 3.533\cdot 10^{-5}$
$SubapArrayWidth = 0.021$
$NumPixelsReqd = 600$

Calculate Required Transmitter Pulse Energy, Et ...

$$Et = \frac{Np\cdot h\cdot \nu \cdot \pi \cdot R^{2}}{\rho \cdot \tau\ atm^{2}\cdot \tau\ opt\cdot Fbeamfill\cdot Asub} \qquad Et = 35.173$$

Calculate Number of Background Photons, Nb (Assume polarization rejection factor of 2X)

$$Nb = \frac{Bg\cdot Asub\cdot \delta\lambda \cdot \Omega\ sub\cdot \tau\ opt\cdot \Delta\ t}{2\cdot (h\cdot \nu)} \qquad Nb = 15.392 \qquad \sqrt{Nb} = 3.923$$

Figure 3. Summary of Modeling Results for Stealth Aircraft Detection System.

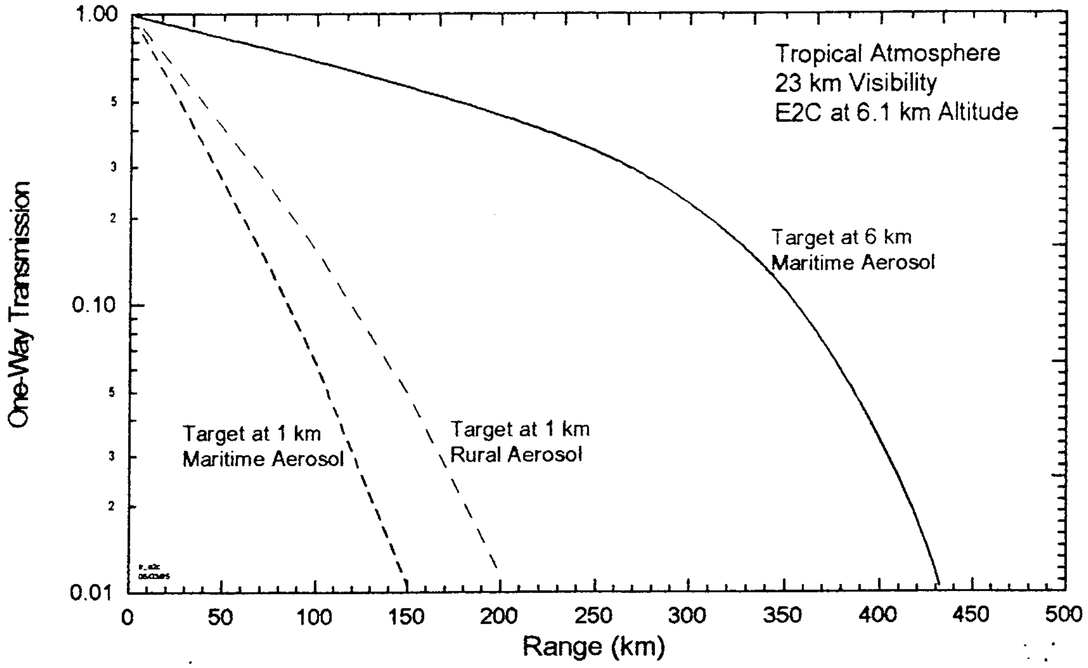


Figure 4. PC-Tran™ 1-Way Atmospheric Transmission for E2C Adjunct Sensor Scenario.

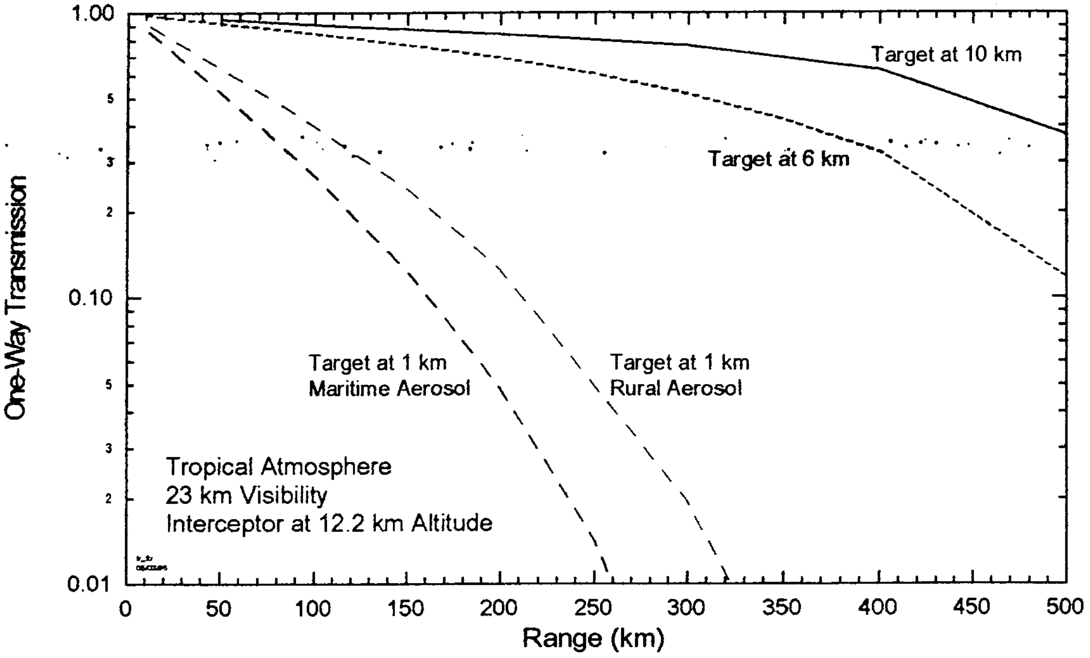


Figure 5. PC-Tran™ 1-Way Atmospheric Transmission for Non-Cooperative Target Identification Scenario.

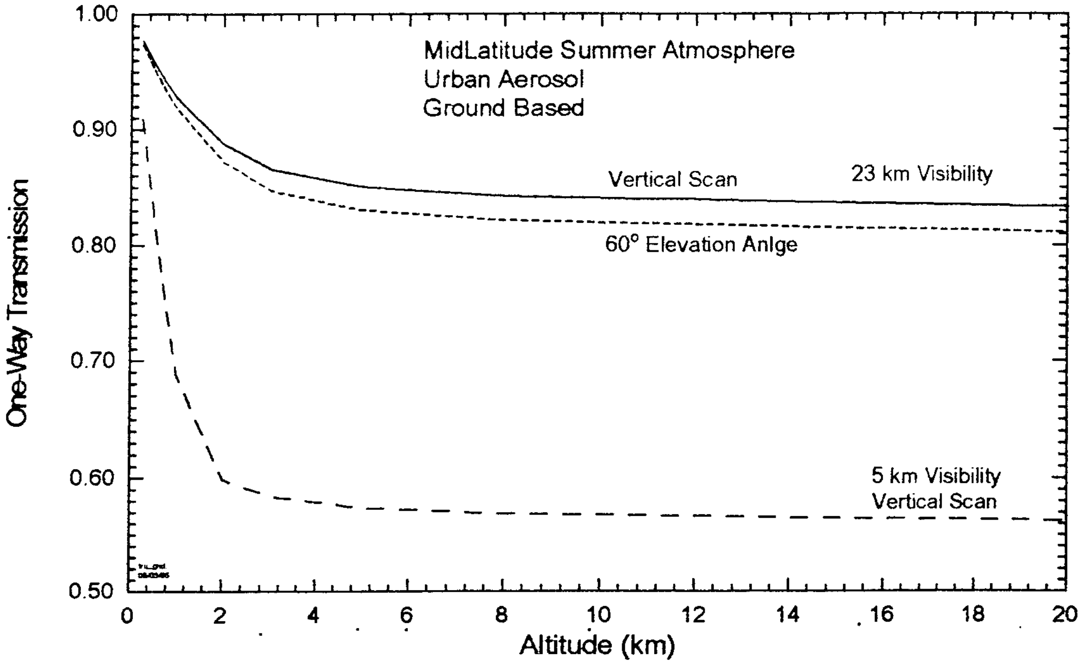


Figure 6. PC-Tran™ 1-Way Atmospheric Transmission for Stealth Aircraft Detection Scenario.

The higher-than-desired pulse energies calculated for the three scenarios led to an analysis of the ASI system equations governing return signal strength. Specifically, the required single-pulse transmitter energy, E_t, can be expressed as:

$$E_t = (h\,c\,\pi) * \left(\frac{mats^2}{mits\,\rho}\right) * \left(\frac{tff}{sffw\ sffl}\right) * \left(\frac{N}{\tau_a^{\,2}\ \tau_o}\right) * \left(\frac{\Delta x}{\lambda^3}\right) \quad (1)$$

where terms are defined as:

Term	Definition
h	*Planck's constant*
c	*speed of light in vacuum*
mats	*max. target size*
mits	*min. target size*
ρ	*target reflectivity*

tff	*transmitter line overfill factor*
sffw	*subaperture fill factor width*
sffl	*subaperture fill factor length*
N	*required number of pre-detection photons*
τ_a	*1-way atmos. transmission*
τ_o	*subap. optical transmission*
Δx	*required target spatial resolution*
λ	*laser wavelength*

Here, it is assumed that the background light level can be controlled to a suitably low level such that its photon shot noise is low compared to the shot noise on the return signal. (An agile subaperture concept has been identified that can achieve background rejection by limiting detector fields of view such that this condition is met.)

The terms in equation (1) deserve comment. The first term, $(hc\pi)$, simply contains constants. The second term, $\left(\frac{mats^2}{mits\rho}\right)$, *shows that the transmitter energy can be reduced by requiring the largest and smallest target widths to be as similarly sized as possible.* Terms 3 and 4, $\left(\frac{tff}{sffw\,sffl}\right)$, $\left(\frac{N}{\tau_a^{2}\,\tau_o}\right)$, concerns system parameters related to transmitter illumination, subaperture sampling fill factors and optical/detector efficiency. The final term, $\left(\frac{\Delta x}{\lambda^3}\right)$, suggests that *longer wavelengths decrease the required pulse energy as do smaller pixel sizes at the target.* This final term provides a great leverage to reduce transmitter power because of the λ^3 term. Note also that the range to the target falls out of the required pulse energy calculation. This is typical for unconventional imager concepts where subaperture arrays scale with speckle lobe sizing.

This analysis led to the conclusion that the auto-correlation speckle imager concept might be optimally used to find identify small targets, like missiles, at great distances using wavelengths longer than 1 μm. To test this idea, the MathCAD™ model was used to predict transmitter power requirements for a system dubbed the "missile hunter." This scenario would employ ASI to image incoming hostile missiles from a point defense location (a Patriot missile battery, say) over distances of 100 km or more. An alternate application would be an F14-based ASI system used to identify incoming missile threats aimed at a carrier battle group at sea.

The MathCAD™ model summary is shown in Figure 7. Here, a laser wavelength of 1.54 μm was assumed because of the eye-safe character of this radiation and the fact that standard low-cost visible wavelength optical technology can be used (i.e. ZnSe, Ge, or other more expensive materials are not required.) The reader should note the dramatic reduction in required pulse energy to levels below 1 J! Note also the small number of subapertures required (40), the exceptionally high spatial resolution (0.15 m, 6"), and the small subaperture array size (1m x 0.5 m) needed to image over the 100 km range. The switch to the 1.54 μm wavelength improves the 1-way optical transmission as illustrated in Figure 8 where PC-Tran™ results are plotted for a ground-based sensor observing a target at 30 km altitude. Background light levels also decrease by about a factor of 3 with the wavelength switch.

In keeping with this approach of increasing the wavelength and decreasing the spread of max. to min. target sizes, the required pulse energies were re-calculated for the E2C adjunct sensor and the non-cooperative target I.D. scenarios discussed earlier. Key results are listed in Table 2 along with the results previously discussed for the "missile hunter" scenario. The results are dramatic and encouraging. The required pulse energies dropped from their former levels by factors greater than ten. In each case the subaperture array sizes remained well within practical limits for the platforms involved.

ASI SPECKLE IMAGER SIGNAL STRENGTH MODEL SUMMARY
Optimized Missle Hunter

User Inputs (in mks)...

Target
$MaxTargSiz = \underline{3}$
$MinTargSiz = \underline{0.5}$
$TargRefl = \underline{0.1}$
$Range = \underline{1 \cdot 10^{5}}$

Atmos & Bgrnd
$Atten1Way = \underline{0.3}$
$Background = \underline{30}$

Transmit
$PulseWidth = \underline{1 \cdot 10^{-8}}$
$TransmitFloodFactor = \underline{6}$

System
$ImgResol = \underline{0.15}$
$Wavelength = \underline{1.54 \cdot 10^{-6}}$

Receiver
$SpectralWidth = \underline{1 \cdot 10^{-8}}$
$RecOpticalTrans = \underline{0.6}$
$\Omega\ sub = \underline{1.904 \cdot 10^{-5}}$
$PrimePhotCnt = \underline{450}$
$SubapLengthFactor = \underline{1}$
$SubapWidthFillFact = \underline{1}$

Intermediate Derived Values ....

$TransApLength = \underline{1.027}$
$MinSpeckleLength = \underline{1.027}$
$SubapLength = \underline{0.513}$
$SubapArrayLength = \underline{0.513}$
$SubapArea = \underline{0.013}$

$TransApWidth = \underline{0.009}$
$MinSpeckleWidth = \underline{0.051}$
$SubapWidth = \underline{0.026}$
$SubapArrayWidth = \underline{1.027}$
$NumPixelsReqd = \underline{40}$

Calculate Required Transmitter Pulse Energy, Et ...

$$Et = \frac{Np \cdot h \cdot \nu \cdot \pi \cdot R^{2}}{\rho \cdot \tau\ atm^{2} \cdot \tau\ opt \cdot Fbeamfill \cdot Asub}$$

$Et = \underline{0.92}$

Calculate Number of Background Photons, Nb (Assume polarization rejection factor of 2X)

$$Nb = \frac{Bg \cdot Asub \cdot \delta\lambda \cdot \Omega\ sub \cdot \tau\ opt \cdot \Delta\ t}{2 \cdot (h \cdot \nu)}$$

$Nb = \underline{1.756 \cdot 10^{3}}$ $\sqrt{Nb} = \underline{41.904}$

Figure 7. Summary of Modeling Results for 1.54 λ Missile Hunter System.

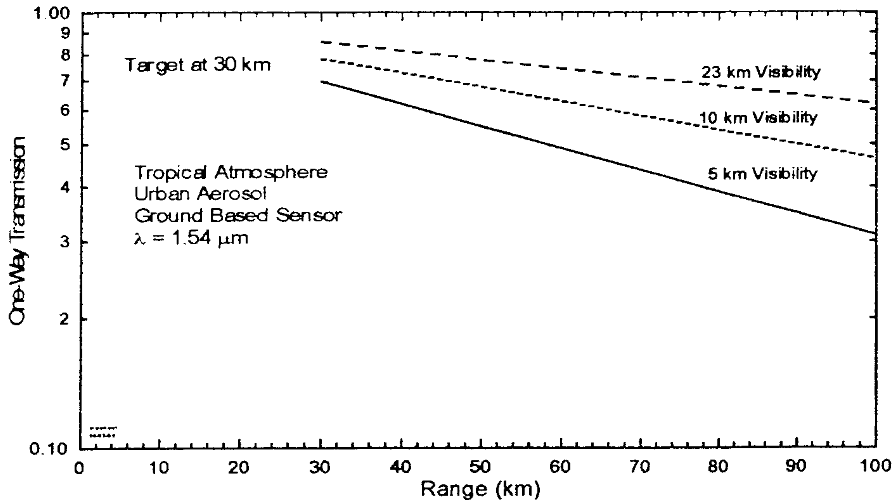


Figure 8. PC-Tran™ 1-Way Atmospheric Transmission for λ=1.54 μm and the Missile Hunter Scenario.

Table 2. ASI Scenarios and Parameters Optimized for Low Pulse Energy at 1.54 μm Wavelength.

ASI Parameter	***E2C Tactical Surveillance Adjunct Sensor***	***Fighter Non-Cooperative Target I.D.***	***Missile Hunter***
Sensor Platform Altitude	6.1 km (20,000 ft.)	12.2 km (40,000 ft.)	0 km (Sea Level)
Worst-Case Viewing Slant ∠	- 40 °	- 30 °	70° from zenith
Max. Target Range	300 km (162 naut. mi.)	150 km (81 naut. mi.)	100 km (54 naut. mi.)
1-Way Atmos. Atten.	0.2	0.2	0.3
Background Level	30 W/m^2-μm-sr	30 W/m^2-μm-sr	30 W/m^2-μm-sr
Desired Resolution at Target	20 cm (8")	20 cm (8")	15 cm (6")
Laser Wavelength	1.54 μm	1.54 μm	1.54 μm
Max. Target Width	20 m	20 m	3 m
Min. Target Width	2 m	1 m	0.5 m
Target Reflectivity	10%	10%	10%
Number of Subaps	200	100	40
Sub. Array Lngth, Wdth	2.3 m x 1.2 m	1.2 m x 0.6 m	1.0m x 0.5 m
Tran Aper. Lngth, Wdth	2.3 m x 12 mm	1.2 m x 12 mm	1.0 m x 9 mm
Req'd Pulse Energy	**11.3 Joules**	**4.5 Joules**	**0.9 Joules**

Investigate Image Quality Through Analysis and Simulation (SOW Item 2)

The entire ASI image simulation software environment nears completion. Approximately 90% of the system has been written and tested to date. The only remaining task involves optimizing the auto-correlation width estimation algorithm to reconstruct the most noise-free images possible. An example of typical ASI image simulation results generated to date are shown in Figure 9.

Develop A Phase II Experimental Plan (SOW Item 4)

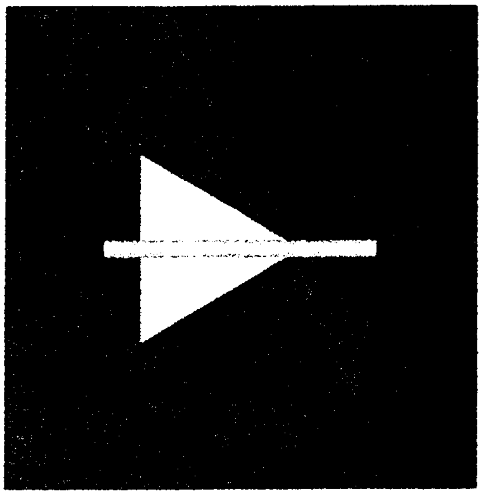
This task will start next reporting period.

Manage Program, Conduct Reviews, Generate Reports (SOW Item 5)

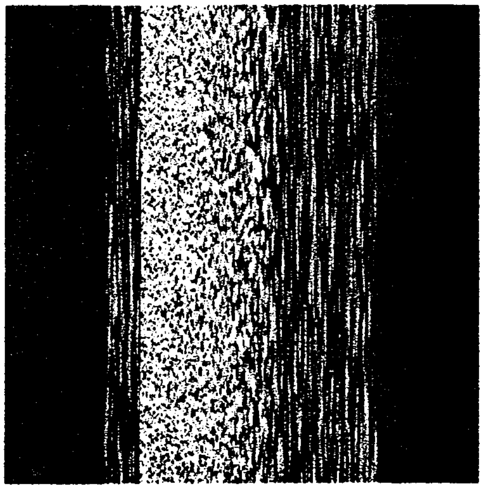
The following Task 5 accomplishments were completed this period:

- The MARCH 95 progress report was compiled.
- The SPARTA subcontract activity was managed. Meetings were held with key SPARTA team members at SPARTA's facility every 7 -10 working days to monitor progress, provide technical input and guide target simulation activities in a relevant direction, based on evolving system analysis results.
- Draft final report materials were generated covering work completed to date.

Starting Image (iftr1)



Speckle Image *(pftr1)*



Auto-correlation *(pftr1cor)*

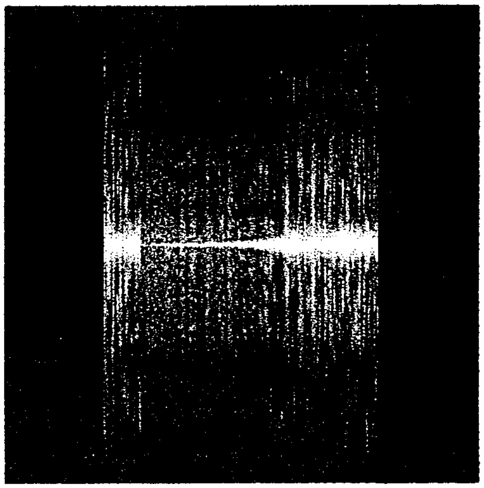


Figure 9. An Example of Typical ASI Image Performance Simulation Results Generated To Date.