



**NAVAL  
POSTGRADUATE  
SCHOOL**

**MONTEREY, CALIFORNIA**

**THESIS**

**COMPUTER-AIDED DETECTION OF RAPID, OVERT,  
AIRBORNE, RECONNAISSANCE DATA WITH THE  
CAPABILITY OF REMOVING OCEANIC NOISES**

by

James R. Fritz

December 2013

Thesis Co-Advisors:

Peter C. Chu

Chenwu Fan

Second Reader:

Ronald E. Betsch

**Approved for public release; distribution is unlimited**

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2013	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE COMPUTER-AIDED DETECTION OF RAPID, OVERT, AIRBORNE, RECONNAISSANCE DATA WITH THE CAPABILITY OF REMOVING OCEANIC NOISES			5. FUNDING NUMBERS	
6. AUTHOR(S) James R. Fritz				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) Ronald E. Betsch, Naval Oceanographic Office 1002 Balch Blvd Stennis Space Center, MS 39529			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB protocol number ____N/A____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words)  There have been three times more attacks to naval ships using sea mines than all other forms combined. Sea mines have always been viewed upon as underhanded and unchivalrous, yet they provide a weaker navy the capability to stall and damage a vastly superior navy. Utilizing unmanned sensors to detect sea mines is the goal of the navy for the future.  Computer-aided detection (CAD) of sea mines is much faster and more consistent than a human operator, yet it 'is not currently being utilized by any of our mine countermeasure assets. Although there are many studies that have incorporated computer aided detection and classification algorithms with sonar imagery for mine warfare, few have used Light Detection and Ranging (LIDAR). During an amphibious assault scenario the ability to land assets quickly and mitigate risk is vital to the success. This thesis analyzes Rapid Overt Aerial Reconnaissance data from an Office of Naval Research experiment by Fort Walton Beach, FL. The CAD algorithm that was developed consistently detects sea mines in LIDAR data while having a manageable false alarm rate.				
14. SUBJECT TERMS Mine Countermeasures, Computer Aided Detection, Computer Aided Identification, Optimization, Physical Oceanography			15. NUMBER OF PAGES 155	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

THIS PAGE INTENTIONALLY LEFT BLANK

**Approved for public release; distribution is unlimited**

**COMPUTER-AIDED DETECTION OF RAPID, OVERT, AIRBORNE,  
RECONNAISSANCE DATA WITH THE CAPABILITY OF REMOVING  
OCEANIC NOISES**

James R. Fritz  
Lieutenant, United States Navy  
B.S., Thomas Jefferson State College, 2004

Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN JOINT METEOROLOGY AND PHYSICAL  
OCEANOGRAPHY**

from the

**NAVAL POSTGRADUATE SCHOOL  
December 2013**

Author: James R. Fritz

Approved by: Peter C. Chu  
Thesis Co-Advisor

Chenwu Fan  
Thesis Co-Advisor

Ronald E. Betsch  
Second Reader

Peter C. Chu  
Chair, Department of Oceanography

THIS PAGE INTENTIONALLY LEFT BLANK

## **ABSTRACT**

There have been three times more attacks to naval ships using sea mines than all other forms combined. Sea mines have always been viewed upon as underhanded and unchivalrous, yet they provide a weaker navy the capability to stall and damage a vastly superior navy. Utilizing unmanned sensors to detect sea mines is the goal of the navy for the future.

Computer-aided detection (CAD) of sea mines is much faster and more consistent than a human operator, yet it is not currently being utilized by any of our mine countermeasure assets. Although there are many studies that have incorporated computer aided detection and classification algorithms with sonar imagery for mine warfare, few have used Light Detection and Ranging (LIDAR). During an amphibious assault scenario the ability to land assets quickly and mitigate risk is vital to the success. This thesis analyzes Rapid Overt Aerial Reconnaissance data from an Office of Naval Research experiment by Fort Walton Beach, FL. The CAD algorithm that was developed consistently detects sea mines in LIDAR data while having a manageable false alarm rate.

THIS PAGE INTENTIONALLY LEFT BLANK

# TABLE OF CONTENTS

<b>I.</b>	<b>INTRODUCTION.....</b>	<b>1</b>
<b>A.</b>	<b>HISTORY OF MIW .....</b>	<b>1</b>
<b>B.</b>	<b>MIW BACKGROUND.....</b>	<b>2</b>
<b>1.</b>	<b>Types of Mines.....</b>	<b>3</b>
<b>2.</b>	<b>MCM Triad .....</b>	<b>3</b>
<b>C.</b>	<b>ENVIRONMENTAL ASPECTS .....</b>	<b>3</b>
<b>D.</b>	<b>INCORPORATING COMPUTER AIDED DETECTION / COMPUTER AIDED CLASSIFICATION (CAD/CAC) INTO COASTAL BATTLEFIELD RECONNAISSANCE AND ANALYSIS (COBRA) .....</b>	<b>4</b>
<b>1.</b>	<b>COBRA .....</b>	<b>4</b>
<b>2.</b>	<b>CAD/CAC .....</b>	<b>5</b>
<b>II.</b>	<b>HISTORY .....</b>	<b>7</b>
<b>A.</b>	<b>REVOLUTIONARY WAR.....</b>	<b>7</b>
<b>B.</b>	<b>CIVIL WAR .....</b>	<b>8</b>
<b>C.</b>	<b>WWI AND WWII .....</b>	<b>10</b>
<b>D.</b>	<b>POST WWII.....</b>	<b>14</b>
<b>III.</b>	<b>MCM BACKGROUND.....</b>	<b>17</b>
<b>A.</b>	<b>MINE CLASSIFICATION .....</b>	<b>17</b>
<b>1.</b>	<b>Method of Delivery .....</b>	<b>17</b>
<b>2.</b>	<b>Location in the Water Column .....</b>	<b>17</b>
<b>B.</b>	<b>ACTUATION METHODS.....</b>	<b>22</b>
<b>1.</b>	<b>Contact .....</b>	<b>22</b>
<b>2.</b>	<b>Command-Control.....</b>	<b>22</b>
<b>3.</b>	<b>Influence.....</b>	<b>22</b>
<b>C.</b>	<b>MCM TRIAD .....</b>	<b>24</b>
<b>1.</b>	<b>AMCM .....</b>	<b>24</b>
<b>2.</b>	<b>SMCM.....</b>	<b>25</b>
<b>3.</b>	<b>UMCM .....</b>	<b>26</b>
<b>IV.</b>	<b>ENVIRONMENTAL ASPECTS OF MIW .....</b>	<b>29</b>
<b>A.</b>	<b>CURRENTS AND TIDES.....</b>	<b>29</b>
<b>B.</b>	<b>BATHYMETRY .....</b>	<b>30</b>
<b>C.</b>	<b>WATER CLARITY .....</b>	<b>30</b>
<b>D.</b>	<b>DOCTRINAL BOTTOM TYPE .....</b>	<b>31</b>
<b>V.</b>	<b>COASTAL BATTLEFIELD RECONNAISSANCE &amp; ANALYSIS (COBRA) ..</b>	<b>35</b>
<b>A.</b>	<b>RAPID OVERT AERIAL RECONNAISSANCE (ROAR) DATA .....</b>	<b>35</b>
<b>B.</b>	<b>FORT WALTON ROAR EXPERIMENT .....</b>	<b>37</b>
<b>1.</b>	<b>CAD/CAC .....</b>	<b>37</b>
<b>VI.</b>	<b>METHODOLOGY .....</b>	<b>39</b>
<b>A.</b>	<b>BACKGROUND .....</b>	<b>39</b>

B.	7 STEPS .....	40
1.	Step 1 Reduce the Search Area.....	40
2.	Step 2 Reduce the Search Points.....	41
3.	Step 3 Calculate the Mean Darkness Value (Rate) within 0.5R Disk.....	41
4.	Step 4 Darkness at Center .....	42
5.	Step 5 Calculate the Mean Value of the Ring.....	42
6.	Step 6 Rate $\geq 0.2$ .....	43
7.	Step 7 $rr + drr \geq 2.2$ .....	43
VII.	RESULTS AND CONCLUSION.....	45
A.	RESULTS .....	45
B.	CONCLUSION .....	52
C.	FURTHER RESEARCH.....	52
APPENDIX A.	SURF MINE LOCATIONS .....	55
APPENDIX B	MATLAB CODE .....	65
A.	FIND MINE.....	65
B.	FIND OBJECT .....	66
APPENDIX C	RESULTS FROM 100 IMAGES.....	73
A.	IMAGES .....	73
B.	TEXT FILE .....	133
LIST OF REFERENCES	.....	135
INITIAL DISTRIBUTION LIST	.....	137

## LIST OF FIGURES

Figure 1.	Attacks on U.S. Navy vessels since the Korean War (from Avery, 1998).....	2
Figure 2.	VTUAV with the COBRA sensor.....	5
Figure 3.	Drawing of the American Turtle, based on Bushnell’s own written description (from Batchelor, 2002).....	7
Figure 4.	Rains Keg Torpedo—The deadliest sea mine in the confederate inventory (from the Harper’s Weekly 1865).....	10
Figure 5.	Paravane used by both the British and American navies during WWI (from Malia, 1991).....	12
Figure 6.	a. The damage to the hull of the <i>USS Samuel B. Roberts</i> on April 14, 1988. b. Image of the <i>USS Princeton’s</i> cracked hull after sustaining damage from a Manta sea mine on February 18, 1991. c. The <i>USS Tripoli</i> after running into a Mk-9 contact mine on February 18, 1991 in the Persian Gulf. ....	15
Figure 7.	Mine Positions in the water column (from Ocean Studies Board, 2000) .....	20
Figure 8.	Mine Warfare Regions (from PEO LMW, 2009) .....	20
Figure 9.	a. MH-53E Sea Dragon helicopter performing mine sweeping operations. b. Avenger-class MCM ship, <i>USS Dextrous</i> (MCM-13) underway. ....	26
Figure 10.	EOD divers neutralizing a moored mine and a MMS in detecting a mine .....	27
Figure 11.	DBT definitions used for MIW making as defined by MCM doctrine (from Ocean Studies Board, 2000) .....	33
Figure 12.	Progression of COBRA development from block I through block III (from Almquist 2009) .....	36
Figure 13.	The initial imagery of a MLO.....	39
Figure 14.	Step reducing the search area.....	40
Figure 15.	Removes areas with large brightness values.....	41
Figure 16.	Object must be greater than .2 of the mean darkness value.....	42
Figure 17.	Reduce the points to only the largest jumps in darkness values .....	44
Figure 18.	Apply the final search criteria to detect MILCOs.....	44
Figure 19.	Moored contact from BAE with algorithm results in lower left corner.....	47
Figure 20.	Small subsurface contact from BAE with algorithm results in lower left corner .....	48
Figure 21.	Large subsurface contact from BAE with algorithm results in lower left corner .....	48
Figure 22.	Multiple subsurface contact from BAE with algorithm results in lower left corner .....	49
Figure 23.	Hedghog subsurface contact from BAE with algorithm results in lower left corner .....	49
Figure 24.	Images that was only partially usable .....	51
Figure 25.	Images of the raw image and then after the 7 step algorithm .....	51
Figure 26.	Images of surface return of the water .....	52

THIS PAGE INTENTIONALLY LEFT BLANK

## LIST OF TABLES

Table 1.	Countries sea mine inventories as of 1999 (from Watts, 1999).....	19
----------	---	----

THIS PAGE INTENTIONALLY LEFT BLANK

## LIST OF ACRONYMS AND ABBREVIATIONS

ABS	assault breaching system
ADCP	acoustic Doppler current profiler
ALMDS	airborne laser mine detection system
AMCM	air mine countermeasures
CAD	computer-aided detection
CAD/CAC	computer-aided detection and classification
COBRA	coastal battlefield reconnaissance and analysis
DBT	doctrinal bottom type
EOD	explosive ordnance disposal
LCS	littoral combat ship
LIDAR	light detection and ranging
MCM	mine countermeasures
MCMC	mine warfare commander
MIW	mine warfare
MMS	marine mammal systems
NAVO	naval oceanographic office
NOMBO	non-mine mine-like object
PMA	post mission analysis
ROAR	rapid, overt, airborne, reconnaissance
SMCM	surface mine countermeasures
SSS	side scan sonar
SZ	surf zone
UAV	unmanned aerial vehicle
UMCM	underwater mine countermeasures
UUV	unmanned underwater vehicles
VSW	very shallow water

THIS PAGE INTENTIONALLY LEFT BLANK

## **ACKNOWLEDGMENTS**

My most heartfelt gratitude goes to Professor Peter Chu for his patience and guidance with endeavor. His insight and love of MIW and advancing our great Navies capability in combating mine threats is inspiring. I would also like to thank Mr. Chenwu Fan his amazing MATLAB skills in developing the CAD algorithm. Thank you, Mr. Ron Betsch of NAVO for being a second set of eyes on this thesis.

Also, I must thank my amazing wife, Carolyn, and my children, Jalyn and Snowden, for your love, support and understanding.

THIS PAGE INTENTIONALLY LEFT BLANK

## I. INTRODUCTION

Naval mine warfare has the ability to enhance a commander's ability to increase combat power while sustaining the current force, conduct operations both offensive or defensive, gain the element of surprise, and gain or restrict key or sea routes. Mine warfare (MIW) is the strategic and tactical employment and countering of sea mines (Joint Chiefs of Staff 1999). Since the Korean War, there have been three times the number of attacks to U.S. Naval ships from mines than all other types of attacks combined as seen in Figure 1 (Avery 1998). A naval mine is one of the most cost-effective weapons and is a force multiplier that can sway the tide of a battle (Ocean Studies Board 2000). On 14 April 1987, an Iranian contact mine crippled the guided-missile frigate *USS Samuel B. Roberts* FFG-58 and incurred \$96 million dollars' worth of damage from a \$1,500 mine that was based off of a 1908 Russian design. A single mine can cause a delay of days or weeks of critical assets and also disrupt sea lines of communication at the same time. Mines can be deployed using aircraft, ships, or submarines, or just by threatening to lay mines. In fact it does not take any mines to create a minefield, if intelligence indicates that there is a high probability that mines have been laid. In January 1980 the "patriotic scuba diver" claimed by telephone to have mined the Sacramento River during the Soviet grain embargo; at which point all shipping movement ceased (Truver 2008). It took the Navy minesweeper *USS Gallant* MSO-489 four days of mine hunting to determine the channel was safe and no mines were ever found. The cost to the port caused by the hoax was estimated in the hundreds of thousands of dollars.

### A. HISTORY OF MIW

Usually sea mines are utilized by smaller or weaker countries or states that do not have a strong navy. The definition of mine warfare is "the strategic and tactical use of sea mines and their countermeasures, including all offensive and defensive mining and protection against mines" (Melian 1991). In our country, sea mines have been used since the revolutionary war when on 6 September 1776, Bushnell's, American Turtle

attempted to attack the British Flag ship *HMS Eagle*. The attempt failed but began led to future attacks on British ships using torpedoes, which we now call sea mines. In the civil war sea mines were the “South’s strategic sea-denial weapon of choice (PEO LMW 2009). During WWI and WWII the use of influence mines became much more prevalent allowing mines to discriminate which ships they target. Post WWII mines have gotten more sophisticated and many older mines have been modified with newer actuation technology making older mines much more useful. The problem that most countries have with MIW is that it cared about and during war time and when an incident happens yet during peace times it may not even be on the back burner.

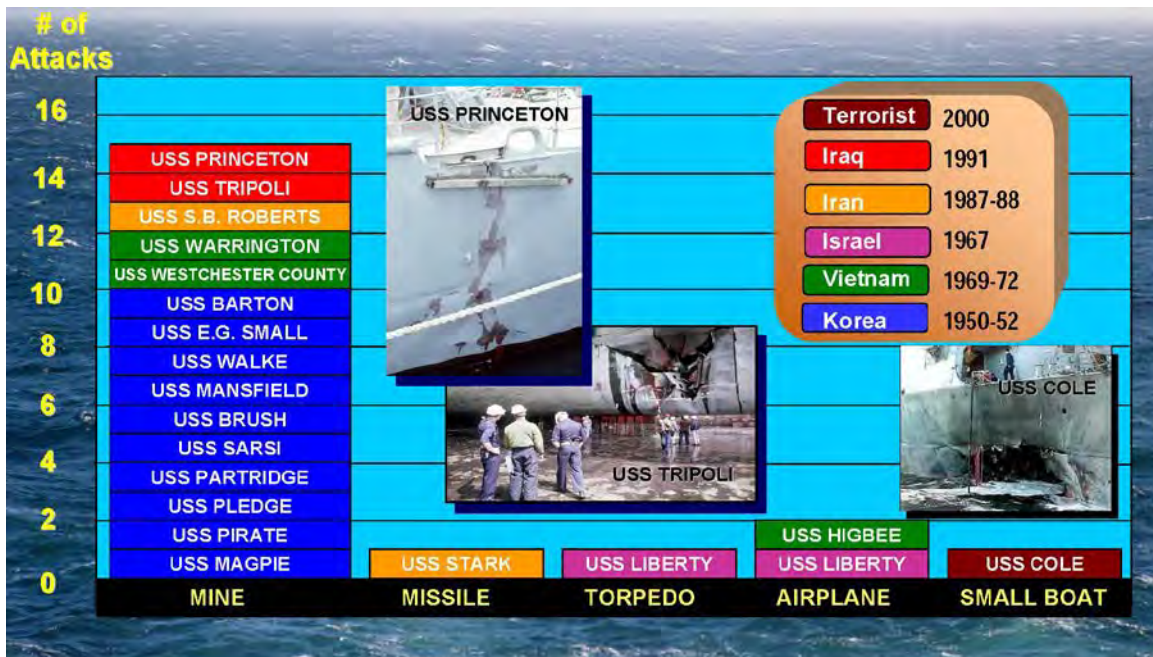


Figure 1. Attacks on U.S. Navy vessels since the Korean War (from Avery, 1998)

## B. MIW BACKGROUND

In MIW, two of the key concerns that a planner has to consider are the type of mines that may be deployed and the environment that the mines are located.

## **1. Types of Mines**

Sea mines are categorized in three distinct ways. First, they are categorized by the way in which they are deployed, whether by air, sea or by submarine. Each of the methods of deployment has its strengths and also its limitations. The second category is where the mines are situated in the water column. Whether they are on the drifting (not moored), moored and the mine is somewhere between the bottom and the surface, and bottom mines. The third category is how the mine is actuated. This can be done remotely, by direct contact with the mine or by a wide variety of electronic actuating devices. A good miner will use each method of deployment to control the battle space.

## **2. MCM Triad**

The MCM Triad encompasses the following areas, air (AMCM), surface (SMCM), and underwater (UMCM). AMCM assets are able to hunt, sweep and neutralize sea mines in a timely manner but operations are limited to day light hours. SMCM assets have the ability to operate around the clock but must stop and prosecute each and every mine like contact (MILCO). UMCM assets are currently the slowest by far but have the ability to hunt virtually undetected and can operate confined waters. Each type of MCM operations has their own strengths and area of expertise and incorporating all areas is a must in order to clear a mine field in a timely manner.

## **C. ENVIRONMENTAL ASPECTS**

To understand how to perform MCM operation a person must understand the environment in which the operations are going to be taking place. The environmental factors of ocean currents, tides, bathymetry, water clarity and doctrinal bottom type (DBT) must be incorporated into the mission plan. When ocean currents are intense the ability to detect and neutralize mines can be impaired. Knowing the tidal variation can impact the ability and what assets can detect obstacles and mines in surf zones prior to an amphibious landing. Bathymetry affects where certain mines can affect our ships and

where there may be routes that are un-minable. The water clarity will impact the ability to neutralize submerged contacts when the optical backscatter is large and diver visibility is less than a few feet. The Mine Warfare Commander (MCMC) must be able to understand how the clutter, roughness, burial of the sea floor factor into doctrinal bottom type (DBT) and how it affects the ability of sensors to locate a mine. When the MCMC knows the environment in which they are operating the ability to detect, classify, identify, neutralize or avoid sea mines increases exponentially.

**D. INCORPORATING COMPUTER AIDED DETECTION / COMPUTER AIDED CLASSIFICATION (CAD/CAC) INTO COASTAL BATTLEFIELD RECONNAISSANCE AND ANALYSIS (COBRA)**

**1. COBRA**

The COBRA program began in the 1990s as a Marine Corp as an advanced technology demonstration (PEO LCS 2011). The program was later transferred to the Navy in 2004 for its detection ability for the Assault Breaching Systems (ABS). By 2009, funding was awarded to procure the low rate initial production units. “The mission of COBRA is to conduct unmanned, aerial, tactical reconnaissance in the littoral barrel space, for the purpose of detecting and localizing mine fields & obstacles in the surf zone and beach zone, prior to an amphibious assault.” The COBRA module will be housed in the MQ-8B Fire Scout Vertical Takeoff and Landing Unmanned Aerial Vehicle (VTUAV) (Figure 2). This VTUAV is part of the Littoral Combat Ships (LCS) MCM mission module and allows operators to be at a safe operating distance while surveying a hostile Surf Zone (SZ) and Craft Landing Zone (CLZ).



Figure 2. VTUAV with the COBRA sensor

The COBRA program is being developed in three blocks with each increment adding onto the increment before. The first block provides detection of surface mines and obstacles in the Beach Zone (BZ) or CLZ during the day (Initial Operational Capability (IOC)/ 2011). In the first block the data has to be downloaded from the VTUAV before the data can be processed. The second block provides night time operating capability and the ability to detect obstacles and mines in the SZ (IOC/2015). The major upgrade in the block two system is the utilization of Rapid, Overt, Airborne, Reconnaissance (ROAR) package that uses a multi-spectral 3-D Light Detection and Ranging (LIDAR) system. The third block will add the capability to detect buried mines and allow for near real time processing (IOC/2018) (Almquist 2009). The problem lies in that all of the increments rely on a human operator to look at the data to determine if there is a MILCO or obstacle present which is very time consuming.

## 2. CAD/CAC

The concept of CAD/CAC being incorporated into MIW is not a new concept and dates back into the mid-1990s (Dobeck et al. 1997). The problem though is that the vast majority of CAD/CAC algorithms deal with sonar imagery, whether they are forward looking sonars or side scan sonars. Sonar imagery has come a long way in the past decade and the resolution is very high. This allows for very in depth and sophisticated

algorithms to be used to find various mine sea mines in varying depths in the water column. The SZ and CLZ is an area that is not able to be surveyed with traditional sonar systems. First the SZ is very turbulent due to wave action which does not allow for sonar systems to be stable enough to acquire usable imagery. The ROAR systems package was developed to operate from the air using a LIDAR system that not only took 2-D imagery but 3-D imagery as well. Since a CAD/CAC algorithm is not currently planned for this type sensor, the goal of this thesis is to develop a CAD/CAC algorithm to find MILCO and obstructions in the SZ and CLZ.

## II. HISTORY

### A. REVOLUTIONARY WAR

The beginnings of MIW in America are attributed to one man, by the name of David Bushnell. He not only created our first limpet style mine, our first mine lines, but also our first “sub-marine,” the American Turtle. His three attempts during the revolutionary war did not damage any British ships, but did show the ability of sea mines to challenge a stronger and larger navy. In 1776, David Bushnell and his brother built the American turtle, so named because it looked like two turtle shells joined together (Figure 3). On the evening of September 6, 1776 Sergeant Ezra Lee positioned the Turtle under the *HMS Eagle*, the flagship of Lord Howe, and attempted to drill a hole and attach its 200 pound explosive. The screw was not able to penetrate the hull because he hit an iron bracing near the keel, and Ezra was forced to retreat as day was breaking. As he retreated, a guard boat gave chase; he released and detonated the explosive/torpedo in his wake allowing him to get away. During the rest of the Revolutionary War, little is known of the exploits of the Turtle, but this was just the beginning for Bushnell.

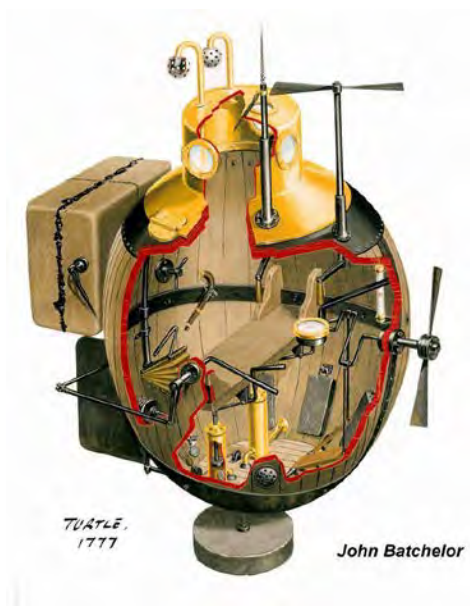


Figure 3. Drawing of the American Turtle, based on Bushnell’s own written description (from Batchelor, 2002)

In August 1777, Bushnell, saw the Cerberus anchored off the coast of Connecticut and devised a way of deploying one of the world's earliest sea mines (Abbass 2008). He planned to attack the Cerberus by sending two floating barrels, filled with explosive, and connect by a line. The idea was to use the prevailing current as propulsion and the Cerberus would run into the line causing the two mines to contact the hull and detonate the barrels. On the morning of August 14, 1777, Bushnell launched the two sea mines, but a schooner that was tied behind Cerberus saw what looked like a fishing line. As the four man crew pulled in the line they found one of the barrels, which they hauled onboard. The sea mine detonated, destroying the schooner, killing three men and wounding a fourth. The Cerberus was unharmed from the explosion.

Bushnell's last attempt to use sea mines in the Revolutionary war took place on the Delaware River on January 7, 1778 (Melia 1991). The approach was going to be similar to the August 1777 mission but without the line connecting any of the sea mines together. The floating gunpowder filled kegs, armed with a simple flint lock actuator were launched down the Delaware River very early in the morning. The problem was that the current was not as fast as anticipated and the kegs did not arrive to the harbor until after sunrise. A couple of British sailors saw and attempted to retrieve one of the kegs, which exploded killing four British sailors. The British forces then began to fire at any and all debris that was floating in the water; causing this battle to be referred to by historians as the "battle of Kegs."

## **B. CIVIL WAR**

There were a few notable advances in MIW prior to the civil war including Samuel Colts electrically controlled mine detonation system and Robert Fulton's moored contact sea mine; both of which were not appreciated or accepted until the civil war began (Melia 1991). When the civil war began in 1861 the union had a strong navy and the confederate navy was still in its infancy. The south realized like so many countries today that sea mines could quickly and with much less cost help balance the power at sea. The Unions Admiral Farragut view point on MIW was, "I have always deemed it unworthy of a chivalrous nation, but it does not do to give your enemy such a decided

superiority over you.” The union viewed the mines as more tedious than a treat at the beginning of the war. Each ship’s Captain had to create his own ingenuity to create MCM devices for his ship and most had none.

The south on the other hand viewed mines as the answer to their weak navy and actively funded MIW to offset there weak navy. The confederacy then set up the Confederate Submarine Battery service which utilized controlled or remote detonated sea mines; followed by funding the Torpedo Bureau in October 1942. A design that is still used today was developed by the Confederate inventor Gabriel J. Rains. Rains created a contact mine, using tarred wood barrels, some with wood cones attached to the both ends (Figure 4). “When the glass and chemical fuse contacted a ship, the chemicals broke into a chamber filled with alcohol and liquid gunpowder and exploded the tightly packed charge of powder housed in the sides of the barrel” (Melia 1991). In other words, he created the first chemical horn actuator which is still used on many contact mines today. By the end of the civil war, the Union realized that the torpedoes were of a threat rather than a nuisance and many Captains would not enter waterways that were potentially mined unless directly ordered to. After the civil war ended the lessons learned, funding for MIW and the officers with MIW experience, disappeared. The knowledge of MIW went back to the way it was before the war which was, “dependent upon the interest of individual naval officers” (Melia 1991).



Figure 4. Rains Keg Torpedo—The deadliest sea mine in the confederate inventory (from the Harper’s Weekly 1865)

### C. WWI AND WWII

At the onset of World War I, sea mines were still contact and remotely actuated but were not only used in shallow waters. The use of sea mines was used very successfully to control sea lines of communication and restrict movement. During WWI there were at least three major advances/inventions in MIW; the British developed the magnetic influence mine and the paravane sweep system, while Germany invented the delayed rising moored contact mine (Melia 1991). Mine warfare was used extensively throughout WWI, but the only new technology that was a game changer was the paravane sweep system.

The British invented a magnetic actuator for a sea mine that allowed a sea mine to reside on the bottom (Melia 1991). So in essence the invention of the magnetic actuator also led to the invention of the first bottom mine. The magnetic actuator works on the principle that every large metal ship while being constructed obtains its own small magnetic field. So when a ship passes over the actuator, it senses the magnetic field and actuates the sea mine. The British viewed these mines as unsweepable so they created them to become inert after a certain period of time and did not use them very often. This type of actuator has been improved upon but is still in use today.

When the Germans invented the delayed rising mine they stumbled onto one of the first counter mine counter measure (CMCM) inventions and one that is still incorporated into some mines today. The reason that it was invented was so that a mine field that was swept by enemy forces and viewed upon as free of mines was in all actuality still active. Mine sweepers would come through with their tow cables and hooks and would possibly find a couple mines but after making a final and not detecting any mines the area would be viewed upon as cleared (Melia 1991). Then the delaying mechanism would actuate and another mine or more would enter into the area where it perceived as clear. Today this technology is used with various influence actuators ranging from a time delay or a ship count before rising into the water column and in harm's way.

The most used invention during WWI and immediately after the war was the Paravane system (Figure 5) (Melia 1991). The paravanes would be deployed in pairs, one on each side of a ship, as the ship moved through the water the paravanes would move away from the ship, the paravanes were connected to the ship by sharp wires that would cut mine mooring as they passed. This caused the moored contact mines to surface whereby they could be neutralized. The paravanes were not used by just warships but also commercial ships so that by the 1918, 2,700 ships worldwide utilized the Paravane (Melia 1991).

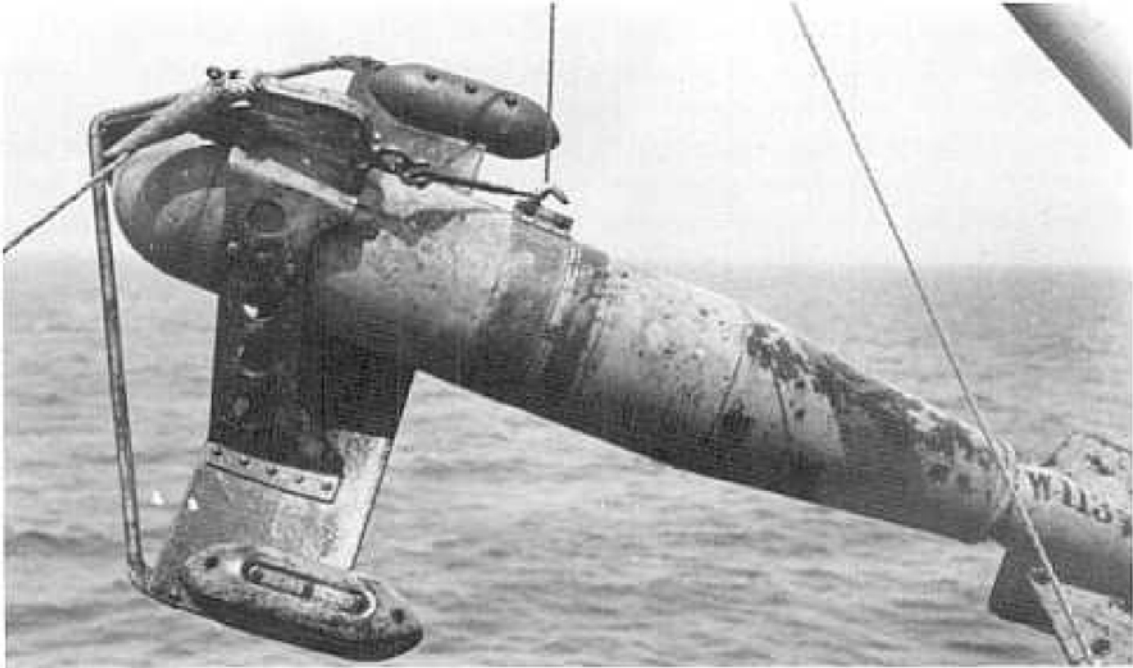


Figure 5. Paravane used by both the British and American navies during WWI  
(from Malia, 1991)

After the end of WWI the United States stopped working on MCM research and little was accomplished until WWII. Within weeks of returning to America, the MCM reserve units disbanded, minesweepers were moth balled, and officers with MCM experience were scattered throughout the fleets. The British on the other hand took the lessons learned and established “an active mine warfare school, developing active and reserve minesweeping fleets, and enhancing the promotion potential of MCM officers” (Melia 1991). This disparity in reaction may have been due to the relatively small number of enemy mines that affected our own home waters. Also after WWI most American officers avoided MIW assignments, “believing quite accurately that it was a road block to promotion” (Melia 1991). The naval exercises that incorporated in a MIW scenarios often had mining and MCM plans that were inconsistent with the actual warfare conditions and often based on practices that were used prior to WWI. During peacetime, only two scientists were responsible for all U.S. Navy ordnance, as a result, MCM suffered and progress remained stagnant (Melia 1991).

The start of WWII brought in a game changer, the introduction of the influence mine. Even though British developed the magnetic actuated sea mine during WWI it was rarely used. At the beginning of WWII Germany began using not only the Magnetic influence mine but the acoustic actuated influence mine and a mine that contained both. The influence mine was predominately a bottom mine that was not able to be swept using the sweep methods of WWI. Since the United States had not conducted much research into MIW since WWI, the United States was woefully behind at the onset of WWII. Germany began utilizing these new mines at the very beginning of WWII when it mined the coast of Great Britain. In September the first British ship sank in an area that was believed to be cleared after sweeping. Shipping losses continued to increase, leading Britain to add magnets to their sweep cables, after correctly suspecting the Germans of reseeded mine fields by air with magnetic influence mines. It was not until a fully functional German magnetic influence mine was unintentionally dropped on a beach that strategies to counter this new mine were discovered (Melia 1991).

In the winter of 1942, German U-boats deployed over three hundred influence mines off Delaware Bay, Chesapeake Bay, Jacksonville, Florida, and Charleston, South Carolina; thereby closing ports for days and forcing the United States to conduct MCM operations in its home waters (Melia 1991). Then in June German submarines reseeded the mouth of the Chesapeake Bay and Hampton Roads, Virginia; sinking two ships, damaging one, and shutting down naval traffic into and out of Norfolk Naval Shipyard for four days. The Navy converted more than 125 fishing ships to mine sweepers in an attempt to sweep the coasts, but still some ports were closed for over a month.

By the end of WWII, the influence mines were becoming more and more advanced. Germany designed a pressure influence mine that was not able to be safely countered without high risk to the mine sweepers (Melia 1991). Many of the mines had combination sensors which had to be actuated more than one sensor. Also some of the mines had ship counters which caused for more a mine to be countered repeatedly before detonating which increased time and cost to clear a mined area. Once again, at the conclusion of the war, interest in MIW was lost due to few experienced personnel remained, lack of interest and lessons went unlearned.

#### **D. POST WWII**

Mines and MCM efforts since the World Wars have increased tremendously. As of today we have the ability to hunt for mines and often times by using a sensor that keeps the sailor out of the minefield altogether. The use of advanced forward looking sonar systems on MCM ships allows for detecting the mine before the mine can harm the ship. The use of AMCM assets to sweep and hunt over a mine field so that a ships are not in danger, is possible. The use of unmanned underwater vehicles (UUVs) to hunt in areas without being detected is another huge advance. Yet with all of these advances the United states has had four times more attacks on ships from mines than all other forms combined (missile, torpedo, airplane and small boat). With all of our advances the sea mine is still the most damaging weapon against our ships.

Of the four most recent attacks on U.S. naval ships, three were from mines. The first was on April 14, 1998, during Operation Earnest Will, the *USS S. B. Roberts* FFG-58 ran into a submerged M-08 moored contact mine (Figure 6). This mine “blew a 20-foot hole in her hull, broke the keel, blew the engines off their mounts, and flooded the main engine room and other spaces” (Melia 1991). The damage to the *USS Roberts* was extensive and required \$96 million to fix and was out of service for 13 months; all from a mine that cost \$1,500 and was designed in 1908 (Khan 2010). Almost three years later the second and third attacks occurred to the *USS Tripoli* and the *USS Princeton* (Figure 6), only a few hours apart. On February 18, 1991 the *USS Tripoli* LPH-10 hit a contact mine 50 miles off of Kuwait (Melia 1991). The mine punched a 16 by 25 foot hole in her hull, but she was able to remain on station. Then a few hours later and 10 miles away the *USS Princeton* CG-59 went over at least one possible two bottom influence mines which lifted ship out of the water and cracked her hull. The damage to the *Tripoli* was quite extensive to the midsection and one of two of the propellers. Both of the mine events that occurred on February 18, 1991 were in areas that were believed to be clear of mines. The total damage to the three ships was in excess of \$123 million. Since the attacks on in 1991 the U.S. MCM fleet has not gotten larger or significantly more modern.

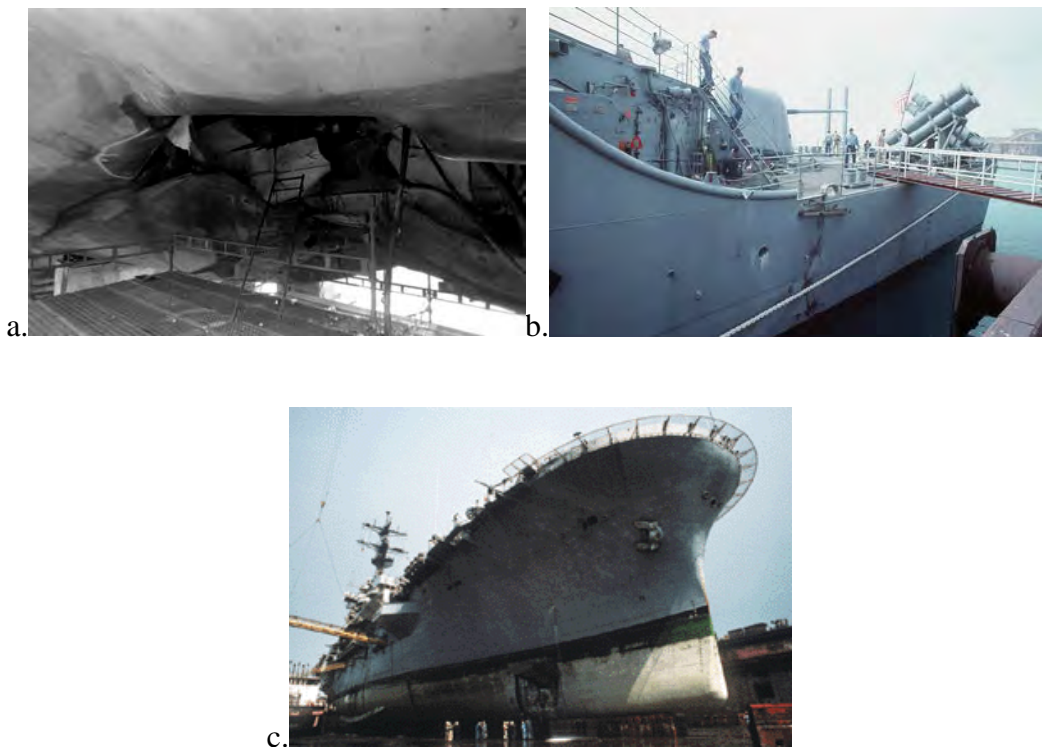


Figure 6. a. The damage to the hull of the *USS Samuel B. Roberts* on April 14, 1988. b. Image of the *USS Princeton*'s cracked hull after sustaining damage from a Manta sea mine on February 18, 1991. c. The *USS Tripoli* after running into a Mk-9 contact mine on February 18, 1991 in the Persian Gulf.

THIS PAGE INTENTIONALLY LEFT BLANK

### **III. MCM BACKGROUND**

#### **A. MINE CLASSIFICATION**

##### **1. Method of Delivery**

One of the first questions that must to be asked when trying to determine what mines an adversary has used in a minefield is what assets they have to deploy the sea mines. Sea mines can be deployed either by air, sea or by submarine, but many mines can be altered to be deployed by different assets. Depending on the assets available to deploy the mines in an adversaries inventory leads to where minefields may be located. When mine need to be deployed rapidly, usually for offensive purposes the preferred deployment method is by aircraft. Aircraft deployed mines can be deployed like bombs and comprise of majority of U.S. Navy arsenal of sea mines. Mines laid by surface assets can be deployed from a variety of ships, boats or even barges, which enables them to be deployed covertly. Submarine laid mines are generally larger in size and cylindrical, because they need to be launched from torpedo tubes. The United States utilizes it submarine launched mines for anti-submarine warfare (Table 1).

##### **2. Location in the Water Column**

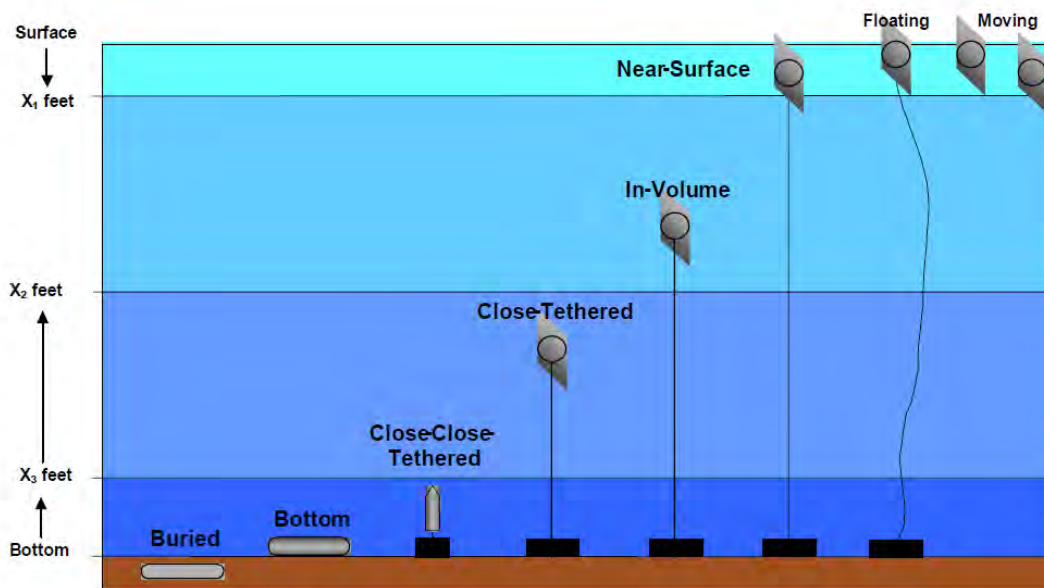
Once you know how an adversary intends to deploy the mines you must concern yourself with were in the water column the mines are located (Figure 7). Just like there are three methods of deployment there are three locations in which the mine can be located. First, there are the bottom mines which can be located from the CLZ all the way to deep water. These mines are negatively buoyant and sink to the sea floor. Depending on the mine type, delivery method, and sediment type of the sea floor, bottom mines can become fully or partially buried. When the mine is not buried they are referred to as “proud” and are much easier to hunt. Due to being negatively buoyant by design the explosive charge can be much larger than that of a moored or drifting mine. The effectiveness of a bottom mine determined by: the depth of water, how large its explosive charge is, and the hull strength of the intended target. So, a small bottom mine, like the Italian made “Manta” (Table 1), would need to be in relatively shallow water (see Figure

8) to be effective against a surface ship. Since bottom mines are the only mines that can be buried, which mitigates the effectiveness of many sonar MCM systems, they can be a very hard mine to hunt (NAVSEA, 2007). Also many countries are now making the mine case look like rocks or have an exterior that promotes sea growth to further limit mine hunting performance.

Country	Name	Type	Description	Length (mm)	Width (mm)	Height (mm)	Weight (kg)	Charge (kg)	Operational Depth (m)
Brazil	MCF-100	Moored contact mine	Can be programmed to remain inert for a fixed period of time, then self-release and anchor itself at the desired depth; can be fitted with an influence sensor.	1,400	1,020	1,500	770	150	3-50
Denmark	MTP-19	Cable-controlled mine	Fully remote controlled; can be operated at distances of 12 km; or roving; consists of a portable weapon control unit, distribution truck and the mine itself.	1,000	1,090	1,170	800	300	3-20
Germany	SM G2	Ground influence mine	Has a non-magnetic casing with acoustic, magnetic, and pressure influence sensors; mine will detonate when preset influence parameters are recognized.	2,000	600	600	750	N/A	N/A
	DM 211	Anti-frogman underwater	Anti-frogman depth charge protects ships and harbor DM 221 signal charge installations against divers; signal charge is used for encoded submarine-to-surface ship communications.	208 DM211 149 DM221	60	60	1.4 DM211 0.8 DM221	0.5 DM211 0.05 DM221	6
Iraq	Al Kaika/16	Free-dive submersible mine	Possibly the largest mine in the world that is designed to destroy offshore structures; operates even in very deep water; timer or remote-control detonation.	3,400	3,400	3,000	16,100	6,000	N/A
	Sege/400	Ground mine	Seabed mine for deep and shallow water for use against medium and large targets; can be ship or helicopter deployed.	700-900	700-900	850	535	400	N/A
Italy	MR-80	Seabed influence mine	Activated by magnetic, acoustic, and pressure influences from the target; body is composed of epoxy resin and glass fibre.	1,646-2,750	533	533	565-1,035	380-865	5-800
	MP-80	Seabed influence mine	Similar influence activation as the MR-80 but with microprocessors to discriminate between targets and countermeasures.	2,096	533	533	760	630	5-300
	Murena	Seabed influence mine	Similar to MP-80 but with an advanced microprocessor firing device.	2,096	533	533	760	630	5-300
	Monta Mine	Shallow seabed influence mine	A dual influence (magnetic and acoustic) anti-invasion mine-shaped to rest firmly on the seabed even in strong flows.	580	580	470	225	150 or 180	2.5-100
	Seppa	Moored influence mine	Programmable mine that can operate in any type of bottom against all types of targets; can select targets and discriminate against countermeasures; can be remotely controlled.	1,560	533	533	670	200	20-300
Russia *	MDM series (MDM 1-5)	Seabed influence mines	Can be laid from a variety of platforms; activated with either acoustic-magnetic or acoustic-magnetic-pressure sensors.	1,530-3,060	450-790	450-790	525-1,500	300-1,350	15-25 to 15-300
	SMDM series	Self-propelled seabed mines	Similar to MDM mines but are placed in the body of a torpedo to be laid by submarines.	7,900 SMDM-1 11,000 SMDM-2	593 SMDM-1 650 SMDM-2	593 SMDM-1 650 SMDM-2	1,860 SMDM-1 5,500 SMDM-2	490 SMDM-1 800 SMDM-2	4-100 SMDM-1 10-150 SMDM-2 200-400
	PMK-1	A combined mine-based on a torpedo	A combined mine based on a torpedo with on-board computer and sensor to identify the target and compute the required trajectory; detonation using combined influence, contact and time fuse.	7,830	533	533	1,850	350	200-400
	M5HM	Conventional shuff mine	Acoustic sensor detects and identifies the target; computes the required trajectory before the underwater rocket is fired to home in on the target.	4,000	533	533	1,500	250	60-300
Spain	MIO-90	Moored influence mine	An intelligent multi-influence mine; parameters can be programmed into the weapon's computer before deployment; incorporates anti-mine-sweeping countermeasures.	1,160	1,090	1,690	1,060	300	5-340
	Mills-68	Naval limpet mine	Time-fused mine that can be used as a demolition charge; attached to underwater structures mechanically or magnetically.	350	250	150	65	N/A	0-40
Sweden	BGM 100 (Rockan)	Anti-invasion ground influence mine	Advanced gliding mine; shape allows cone-laying over a wide area while covering the minimal silencing loop profile; shape makes it difficult to detect; constructed of reinforced plastic.	1,015	800	965	190	105	5-100
	BGM 80	Moored influence mine	Programmed to anchor itself automatically at the desired depth before firing.	1,125	660	1,125	450	80	20-200
	BGM 601	Ground influence mine (bunny)	Developed as a submarine weapon to be attached to the exterior; incorporates multiple sensors with sophisticated logic making it resistant to countermeasures.	2,000	750	750	300	80	20-200
	BGM 600	Cable-controlled mine	Developed to provide a rapid means of deploying a controlled minefield.	1,700	600	700	700	200-400	N/A
United Kingdom	Sea Urchin	Programmable influence mine	An intelligent seabed mine that can be programmed to detonate by a range of influences when the target is at the closest approach point.	1,440-2,940	533	533	569	350	5-200
	Stonefish mine	Ground influence mine	Designed to be modular to fit any requirements; detonation by acoustic, magnetic, and pressure sensors with signal processing capabilities.	2,500	533	533	990	600	10-200
United States	Mk 32, 55, 56, and 57	Seabed influence mines	These mines are now obsolete although many are still in inventory; activated using magnetic, acoustic, and pressure devices.	2,250-3,000	844-1,060	844-1,060	542-1,010	800-676	45-350
	Mk 36, 40, 41, and 115A	Air-launched influence mines	Detonated using magnetic and acoustic sensors; and 115A intended for use in shallow water; obsolete although many are still in inventory.	2,250-3,030 1,15A-450	400-630	400-630	240-926 1,15A-61	24-204	45-91
	Quickstrike series	Air-launched seabed mine	Group of mines with different cases but common target detection and classification (radar) based on conversion of existing ordnance.	2,200-3,600	271-884	271-884	227-908	69-202	<100
	Mk 60	Encapsulated torpedo	A Mk 46 torpedo inserted into a mine casing; used for anti-submarine warfare; can classify targets and initiate the release of the torpedo; employs both passive and active sensors.	3,700	533	533	1,075	45	≈305
	Mk 67 SAMM	Air-launched seabed influence mine	Self-propelled mine for use in shallow water and where covert mining is desirable; detonation using magnetic, acoustic, and pressure sensors.	4,020	495	495	745	N/A	<100
Yugoslavia	M66	Diversionsary underwater mine	Newly non-magnetic housing; timed fuse; settings once armed and activated cannot be removed.	670	430	320	50	27	30
	M70	Acoustic influence seabed mine	Employs highly sensitive sensors with a large explosive charge; can be laid from multiple platforms.	2,928	594.4	594.4	1,000	700	50-150
	M-71	Limpet mine	Attached magnetically and mechanically; fitted with a time fuse.	345	345	245	14	3	30

N/A = information not available or not provided. \* All known Russian mine types are not discussed here; for a more complete list refer to Jane's Underwater Warfare Systems. Source: Watts, 1999.

Table 1. Countries sea mine inventories as of 1999 (from Watts, 1999)



where  $X_1$ ,  $X_2$ , and  $X_3$  vary depending on the particular MCM system.

Figure 7. Mine Positions in the water column (from Ocean Studies Board, 2000)



Figure 8. Mine Warfare Regions (from PEO LMW, 2009)

Sea mines can also be located in the volume or in simple terms tethered somewhere between the surface and the bottom. This can be accomplished by having a positively buoyant mine that is tethered to an anchor/mooring. The length of the tether along with the crush depth of the mine case limits the depth at which the mines can be placed (NAVSEA 2007). The explosive charge and actuating mechanism are both located in the mine case. Since the case is positively buoyant, the amount explosive is less than that of a bottom mine, thereby reducing its effective damage radius. The Volume mines are designed to be effective against submarines and surface ships. Since moored mines have a long cable that attaches the mine to its mooring they are susceptible to mechanical mine sweeping (cutting of the tether). They can be moored very close to the surface so that even small boats with a very shallow draft can be at risk. There are two very interesting types of moored mine, homing or guide mines and the rising mine. The homing mine is similar to a moored torpedo or missile that once triggered it is guided to its target. The rising mine is a deeper moored mine but once it is triggered the mine case is released and the mine rises to the surface and detonates.

Moving mines or drifting mines are positively or neutrally buoyant mines that are deployed in a way to be able to move with the currents. Drifting mines that are no longer tethered to their mooring are classified as floaters (NAVSEA 2007). True drifting mines have been banned by the 1907 Hague treaty, yet have been used on occasion since then. The advantage of drifting mines is that they can be deployed in any water depth and be effective. The main drawback of drifting mines apart from being banned is that they will travel randomly and possibly damage friendly and neutral shipping traffic as well as your adversaries. Consequently, drifting mines are usually fitted with a scuttling device that will cause the mine to sink and become inert after a certain period of time. Drifting mines may be located at the water surface or at a set depth below the surface by using a depth-controlling hydrostatic device. Often drifting mines will be attached to some innocent looking object like an abandoned boat or tethered to each other to increase probability of hitting a ship.

## **B. ACTUATION METHODS**

### **1. Contact**

Contact mines are the oldest and the most commonly seen mine that explosive ordinance and demolition (EOD) divers are neutralizing. The mine casing or a contact mechanism attached to the case must make contact with a ship or object for the mine to detonate. Contact mines have come a long way since the revolutionary war but the overall theories remains the same, sit and wait for a ship to run into it and blow up. The actuating mechanisms have gotten much more sophisticated and can be dormant in the water for long periods of time because they are not actively sensing or searching for a target. Contact mines that utilize a chemical horn can be harmful for many years after being deployed. The chemical horn contains a fragile vile of electrolyte, when the horn is struck the electrolyte flows into the battery, and energizes the firing circuit (NAVSEA 2007). They are fairly simple and the least expensive mine, yet have caused almost \$100,000,000 in damage to the U.S. Navy over the past 15 years.

### **2. Command-Control**

Command-control or remote operated sea mines can be detonated by way of a command signal. This signal can be sent either wirelessly or via a cable from a land based control center (NAVSEA 2007). Controlled mines can be made safe, live or to detonate by the user a t any time. Controlled mines can also be influence mines and be armed when the user sends a signal. They can contain detection devices that signal a ships presence and allow the user to choose when to detonate. Command control mines are traditionally used defensively to protect harbor approaches but can be used offensively when controlled wirelessly.

### **3. Influence**

Influence mines are actuated from a target created influence in the vicinity of the mine or by certain responses from active signals from the mine (NAVSEA 2007). The sensitivity setting can be adjusted on the mine to fine tune the mine for a specific type of ship or to reduce background noise in the location that it will be deployed. Influence

mines can be actuated from a variety of changes in the physical environment caused by a target's presence, such as magnetic, acoustic, and pressure. When a certain signal or combination of signals is detected, a signal is sent to the firing circuit to determine if the mine should detonate. Usually influence mines have two or three sensors and the most common combination being magnetic and acoustic. Since a combination of signals may be necessary for the mine to detonate makes the influence mine a very difficult mine to neutralize by sweeping. Also the use of more than one sensor provides better target discrimination.

The magnetic sensor was the first influence mine that was developed in WWI by the British. The sensor was designed to sense a change in the Earth's magnetic field when a target passes by. The sensor monitors a change in magnitude of the magnetic field. The two types of magnetic sensors used today are utilizing an induction coil or magneto-resistant fluxgate.

The acoustic sensors consist of passive hydrophones and a processing unit that detects underwater sounds and active transponders (NAVSEA 2007). The hydrophone is a passive system that listens for a noise generated by a target's engine, propeller, or machinery. The transponder is an active system that sends out an acoustic signal at a suspected target to determine the validity of the target. Every ship, submarine and boat puts out its own unique acoustic signal which can be exploited by an acoustic mine. Acoustic mines are very versatile and can be designed to operate passively to sense sounds from low frequencies (less than two Hz) to high frequencies (greater than 15 kHz) or can be active in which they use an active sonar to locate a target.

A pressure sensor reacts to the hydrodynamic pressure field of a target as it passes (NAVSEA 2007). The pressure sensor is very susceptible to surface waves and as such is used in combination with other sensors. The pressure sensor monitors the slight hydrostatic pressure change caused by a passing ship while ignoring the large variation caused by waves. The huge advantage of this system is that it is impossible to simulate the pressure signature of the target ship, which makes it very hard to sweep.

## C. MCM TRIAD

### 1. AMCM

The airborne contingent of the Navy's MCM "triad" is comprised of two squadrons of MH-53E Sea Dragon helicopters (Figure 9) and a total of 28 helicopters. Both squadrons (HM-14 & HM-15) are being collocated at Naval Air Station Norfolk. The helicopters conduct minesweeping, mine hunting, and neutralizing operations; and can be airlifted anywhere in the world within 72 hours (PEO LMW 2009). The AMCM approach to MCM operation is one asset will conduct detection/classification operations and a follow on asset will conduct the neutralizing portion; this referred to as "bumper pool." (NAVSEA 2007) The Sea Dragons use the following MCM systems:

- AQS-24: multi-beam side-looking mine-hunting sonar detects and classifies all types of seam mines in the water column. (PEO LMW 2009)
- Airborne Laser Mine Detection System (ALMDS): allows MILCO's to be identified as mines or non-mine mine-like bottom objects (NOMBOs) (NAVSEA 2007)
- 
- Mk 2(G): Acoustic Sweep often referred to as "rattle bars," consists of parallel fixed and swinging pipes or bars that collide to produce medium- to high-frequency acoustic energy that detonates acoustic mines. (NAVSEA 2007)
- Mk 103: Mechanical Sweep system is a modified consists of a rugged tow wire, chipper cutters, a depressor, otters, floats, and float pendants to target the mooring cables of shallow-water moored mines. (PEO LMW 2009)
- Mk 104 Acoustic Sweep is a self-rotating cavitating disk inside a venturi tube that generates cavitation sound signatures similar to a ship as it is towed by the helicopter, used to counter acoustic mines. (PEO LMW 2009)
- Mk 105 Magnetic Sweep is an open-loop electrode to counter magnetic bottom mines. The Mk 105 consists of a gas turbine generator mounted on a hydrofoil sled. The generator produces direct current through the electrode array to create a magnetic field that replicates the magnetic signature of a surface ship. (NAVSEA 2007))
- Mk 106: Combination Sweep uses both the Mk 104 and Mk 105 sweeps and is effective against acoustic and magnetic mines.

## 2. SMCM

The dedicated U.S. SMCM fleet comprises of 13 Avenger (MCM-1)-class ships as seen in Figure 9. Four are forward deployed in Bahrain, three are homeported in Japan; and the remaining seven are homeported in San Diego, California at the new Mine Warfare Center of Excellence. The avenger class ship like are able to perform sweeping, hunting and neutralizing of sea mines. The SMCM approach to MCM is that once an asset detects/classifies a MILCO, the same asset will identify and neutralize the contact before proceeding; this is referred to as the “blow as you go.”(NAVSEA 2007) The Avenger-class ships are fitted with several systems to carry out mine countermeasures operations:

- SQQ-32 variable-depth mine detection and classification sonar: This is a variable-depth sonar (VDS) that employs both a forward looking sonar (FLS) for detection and a scanning high-resolution sonar for classification. The sonar system can detect and classify moored and bottom mines. (NAVSEA 2007)
- SLQ-37 Magnetic/Acoustic Influence Minesweeping System: Consists of an M Mk 5A open-loop electrode sweep combined with a TB 27 (for low frequency) or TB 26(for medium frequency) acoustic sweeping system to counter magnetic and acoustic mines. (NAVSEA 2009)
- SLQ-38 (Mechanical) Minesweeping System: Is designed to cut the mooring cable of moored mines that are near the surface. The SLQ-38 uses a rugged wire and cable cutters, and can be rigged on one or both sides of the minesweeper. (PEO LMW 2009)
- SLQ-48(V) Mine Neutralization System (MNS): Is an unmanned submersible that can neutralize bottom and moored mines. After a contact is detected, the MNS is put in the water to reacquire the target, a low-light-level television is then used to classify, and identify the contact. If the contact is identified as a mine, the MNS places an explosive charge next to the mine, the MNS is recovered, and the explosive charge destroys the mine. If the contact is a moored mine, the MNS will attach a charge on the cable near the mine case or cut the cable to allow the mine to surface, where it is neutralized. (PEO LMW,2009)

The problem with the Avenger surface mine countermeasures vessels are beyond the midpoints of their service lives, and the littoral combat ship (LCS) with its MIW module is not operational.



Figure 9. a. MH-53E Sea Dragon helicopter performing mine sweeping operations.  
b. Avenger-class MCM ship, *USS Dextrous* (MCM-13) underway.

### 3. UCMC

The third component of the “triad” is the underwater mine countermeasures (UMCM) force which comprises of the Navy’s EOD detachments that specialize in handling of unexploded ordnance (Figure 10). EOD MCM personnel directly support mine-hunting and clearance operations using specialized countermeasures-unique equipment to locate, identify, neutralize or recover sea mines or underwater improvised explosive devices (UIEDs). EOD personnel use hand-held sonars, various unmanned underwater vehicles (UUVs) equipped with side scan sonar (SSS), and the Marine Mammal System (MMS) with its inherent, organic sonar capability. When EOD recovers an adversaries mine, it can be disassemble to determine how they work, type of sensors used, setting for the sensors, and the mines intended target. Then Based on these data and assessments, the MCMC can better utilize the MCM resources. Synthetic Aperture Sonar (SAS) on UUVs are now in the tested phase and will provide a long-range, faster coverage rate, and higher-resolution sonar than the SSS that is used today. The MMS is the best performing minehunting system in the Fleet and can even find buried mines (Figure 10). These specially trained bottlenose dolphins and sea lions excel in mine detection and neutralization, swimmer defense, and recovery of mines, torpedoes, and

other objects. Unfortunately, the area coverage rate of the MMS is low and the logistics to bring in a MMS system is very high. EOD personnel provide a wealth of information about an adversary's mines and their capabilities.

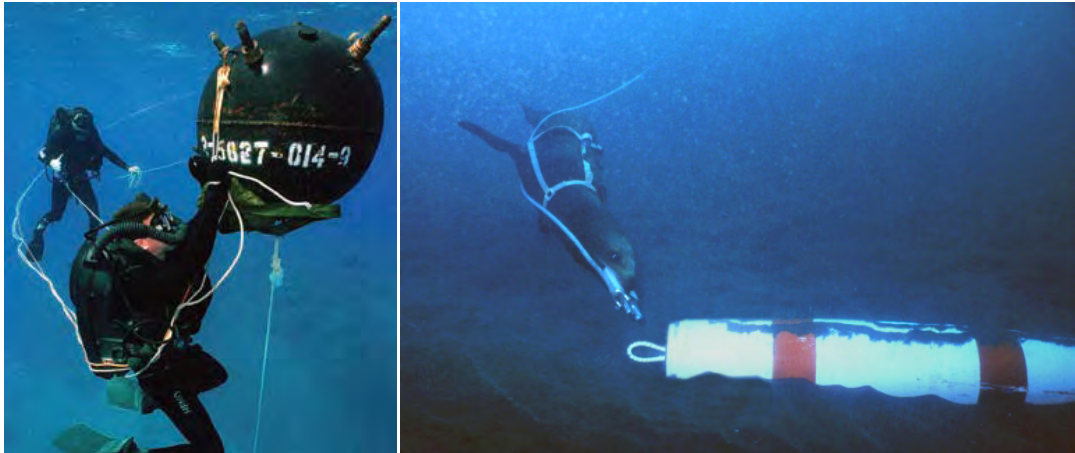


Figure 10. EOD divers neutralizing a moored mine and a MMS in detecting a mine

THIS PAGE INTENTIONALLY LEFT BLANK

## **IV. ENVIRONMENTAL ASPECTS OF MIW**

### **A. CURRENTS AND TIDES**

In MIW currents and tides play a large part because they directly influence the ability to neutralize mines and to some degree the ability to detect mines. Currents are flows of water that take place over time, and comes from different processes such as tides and direct wind forcing. Many UMCM mine hunting assets are limited by strong currents especially currents that are tidally influenced in harbor channels and shipping routes. Most MNVs and EOD divers have relatively low limits with regards to currents and when currents are near the operational limits the time needed to perform tasks can be extended.

Currents are long-time-scale fluid flows arising from a wide variety of processes, such as seawater density gradients, direct wind forcing, and tides. Meteorological and oceanographic analysis, prior to mine warfare activities in the coastal zone, must be sophisticated enough to understand the complexities of forces driving current flow, determine how these forces are interacting with each other, understand the time scale of variability driving current flow, and understand how this may affect the mission (Ocean Studies Board, 2000). When currents are high moored mines may become submerged or drift (do to moving of the anchor), whereas if currents are less extreme the mines may be surfaced and the mooring not drift. Drifting mines rely on currents to move them into location like ports and harbors or in channels or restricted water ways, which are often over a hundred miles from where the mines were deployed. To fully take into account how to best work within limitations of unites in depth tidal and current models must be used. This has been known by many units and requests for current and tidal models from the Naval Oceanographic Office (NAVO) is usually requested for MIW support

Tides vary from place to place and in some location the changes in sea surface depth is very small, but in other locations, like the Bay of Fundy, the fluctuation can be over 50 feet. Tidal effects are relevant to MIW operations when the depth of water is shallow as in the VSW and the SZ but also in the ports and harbors where tidally driven current can easily exceed three knots. Mines and obstacles in the SZ can be submerged

and not visible while the tide is high, but be when the tide goes out the SZ minefield may be fully exposed. In the surf zone the ability to neutralize obstructions and mines is dependent on the water depth and of when MILCO that are being prosecuted are in the wave breaking region the mission becomes very complex. Timing missions around tides and low currents is a must for successful and safe operations (Ocean Studies Board 2000).

## **B. BATHYMETRY**

The bathymetry or water depth can influence the strength of currents, the location and size of breaking waves and the tidal range (Ocean Studies Board 2000). In the SZ changes in bathymetry occur with the tide, while in deeper waters changes in bathymetry occur at much slower rates. By looking at the bathymetry, one can see the deeper channels that are conducive to stronger currents and plane operations accordingly. Also when there is an offshore bank, the areas adjacent to the bank will experience focusing of surface waves which can be detrimental to diver operations (Ocean Studies Board 2000). Knowledge of the bathymetry in the SZ and VSW regions is key for UCMC operations.

Bathymetry is a boundary condition for near shore waves and currents which lead to scouring and or burying of mines (Ocean Studies Board 2000). The more mine are scoured the harder it is for mine detection and many sensors of mines are not seriously impacted by burial making the mines just as effective. The bathymetry also affects the location that certain mines can be effective and where there are large fluctuations in bathymetry mines can drift to deeper areas where they may be more or less effective. When there is a significant slope in bathymetry the mines can be funneled to the bottom of a channel; when this happens, there can be a lot of other clutter making the mines very hard to find. Understanding the bathymetry allows the MCMC to better plan operations around mined areas.

## **C. WATER CLARITY**

Water clarity is very important to UCMC EOD divers and their ability to detect, classify, identify, re-acquire and neutralize mines. Water clarity does not just affect the EOD divers but every branch of the MCM triad because when water clarity is extremely

poor the ability to neutralize mines is very difficult because the MNVs utilize optical sensors. Water clarity is determined by many factors including, absorption and scattering by phytoplankton, suspended sediments, detrital particles, and dissolved organic material (Ocean Studies Board 2000). The scattering of light by these particles obscures the ability to see the mines and obstacles, while the absorption of light by the same particles darkens the area which also decreases visibility. Another element that factors into visibility is the type of sediment that is on the ocean floor because if a diver or MNV disturbs the ocean floor the water clarity can be adversely affected. Understanding what effects and how water clarity affects operations is critical to planning and creating reasonable timelines.

#### **D. DOCTRINAL BOTTOM TYPE**

Doctrinal bottom type (DBT) is broken into three parts, roughness, clutter, and bottom composition. All three parts affect MIW and the ability to detect and classify mines. Roughness is a measure of the ridge or sand wave height in an area. Clutter is the Non-Mine, Mine-Like Bottom Objects (NOMBOs) density occurring in a square nautical mile. Bottom composition is broken into three categories, rock, mud and sand, but also adds the amount of burial as a discriminating factor. Once all three parts of are taken into account a letter and number designator are given per Figure 11.

Roughness is determined by the amount and height of sand ridges in an area. Large amounts and relatively tall sand waves affect side scan sonar (SSS) imagery in very negative ways by causing shadow regions that can mask or obscure mines. If a mine shape is located between two sand ridges the mine may not be able to be detected because the size and shape that is seen in the imagery could not appear to be mine like. There are three categories of roughness, smooth(less than 20cm), moderate (20cm through 30 cm), and rough (greater than 30cm). Areas that are smooth are better for MCM operations while rough areas are not.

Clutter is the number part of the designator and its value is not influenced by the other two parts. Getting the clutter value is very straight forward and is determined by how much debris and trash that may appear to be mine like but are not that are on the ocean floor. When the number of NOMBOs is less than four per square kilometer that the

clutter value is 1, greater than four and less than 12 NOMBOs per kilometer the value is 2, and when there are greater than 12 NOMBOs per kilometer the value is 3. When the value is higher the ability to hunt becomes more difficult because it of a much larger amount of objects on the ocean floor that appear to be mines.

Bottom composition is the most important aspect of DBT because it has burial included as one of its attributes. The amount of burial can change an area from huntable to unhuntable where clutter and roughness can only change the amount of effort that needs to be applied. Bottom composition brings in roughness and provides the letter designator for the DBT, which is the bottom category. Bottom categories range from “A,” which is the optimum minehunting seafloor, to the worst case of “D,” which is typified as a high burial environment (Ocean Studies Board 2000). The Bottom composition is broken into three sediment types, rock, mud, and sand. When the sediment type is rock there is no burial but the bottom category starts out at “B” and is often difficult to detect MILCOs do to large rocks obstructing SSS imagery. Mud and Sand are usually better for minehunting except when the burial is greater than 75 percent because the amount of mine that is visible has decreased to the point where they are very hard to detect. As per Figure 11, the DBT for an area with 11 NOMBOs per square kilometer, 25 cm sand waves, and rocky sediment, would be “C-2.”

## *MCM Doctrinal Bottom Definitions*

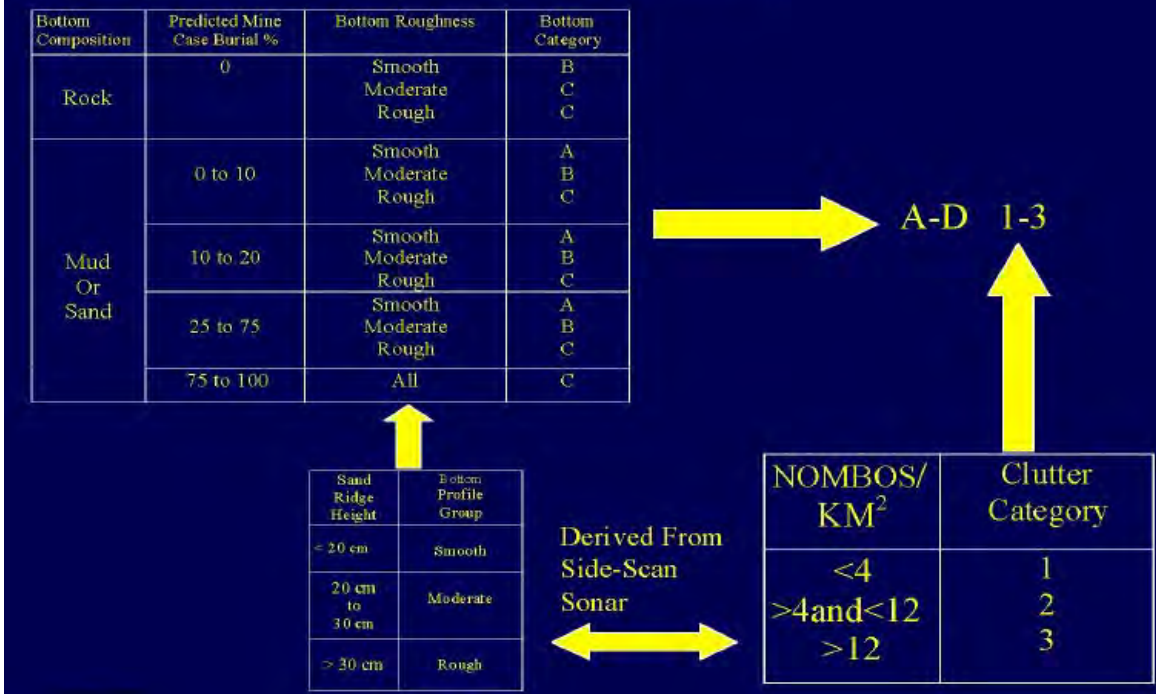


Figure 11. DBT definitions used for MIW making as defined by MCM doctrine (from Ocean Studies Board, 2000)

THIS PAGE INTENTIONALLY LEFT BLANK

## **V. COASTAL BATTLEFIELD RECONNAISSANCE & ANALYSIS (COBRA)**

### **A. RAPID OVERT AERIAL RECONNAISSANCE (ROAR) DATA**

Mine warfare is a balance of time versus risk. In effort to reduce the amount of time and risk involved in mine countermeasures, it is in the interest of the warfighter to unmanned aerial sensors to detect moored and submerged target in a given location of interest. The ROAR sensor is part of the COBRA program and the COBRA program is part the detection capability for the ABS (PEO LCS 2011). COBRA's mission is to conduct unmanned, aerial, tactical reconnaissance in the littoral battle space to detect and localize mine fields and obstacles in the surf and beach zones prior to an amphibious assault (PEO LCS 2011). The COBRA module will be housed in the MQ-8B Fire Scout Vertical Takeoff and Landing Unmanned Aerial Vehicle (VTUAV) (PEO LCS 2011). This VTUAV is part of the littoral combat ships (LCS) MCM mission module and allows operators to be at a safe operating distance while surveying a hostile surf zone (SZ) and craft landing zone (CLZ).

The capability progression of COBRA is broken into three initial increments (blocks) of development with each introducing new or enhanced capabilities (Almquist 2009). Block I is a passive system with capabilities of daytime surface-laid mine line and obstacle detection in the beach zone, limited detection capability in surf zone, and off-board processing (Figure 12). Block II will add night-time minefield and obstacle detection capability and full detection capability in surf zone (Figure 12). Block III will add buried mine line detection capability and near real-time onboard processing (Figure 12). None of the increment involve a computer aided detection and classification (CAD/CAC) algorithm, thereby requiring all of the data to be analyzed by a human operator to detect the mines and obstacles.

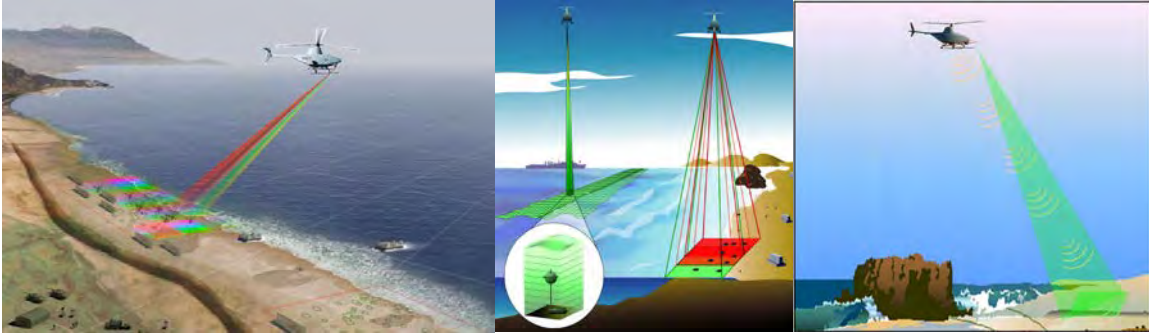


Figure 12. Progression of COBRA development from block I through block III (from Almquist 2009)

The block I COBRA module will consist of three primary components, the sensor module, Post Mission Analysis (PMA) station, and a Tactical Control System (TCS) for the VTUAV ground control station. The ground control station will be able to plan the flight plan, monitor and reprogram the flight path depending on the needs of the mission. The Block I key components include a highly stabilized, step stare, digital gimbal, high resolution multispectral imaging digital camera with spinning six-color filter wheel, a processing unit, and a solid state data storage unit. The overall payload weight of the cobra module weighs less than 150 pounds. At the end of each mission the data on the data storage unit is exported onto the COBRA PMA station onboard the LCS to be analyzed. The sensors will have detection capability in the BZ during the day time.

The block II COBRA module will incorporate the ROAR system will use a Lite Cycles Incorporated (LCI) integrated scanner, detector, and telescope (ISDT) (Almquist 2007). The new sensor will allow for night operations and add the detection capability in BZ, SZ and VSW regions. This new module will utilize an active multi-spectral true 3-D LIDAR system that is optimized for day and night time operations in the SZ (Almquist 2012). The Sensor will have a multi-look scan pattern for operations in high-clutter SZ environment to help reduce the number of false alarms. The size of the block II system will also be very compact so that the module will be able to on a tactical unmanned aerial vehicle.

The block III will add buried mine field detection in the BZ as well as near real time data processing (Almquist 2012). The module will utilize active and passive imagers

and a Laser Interferometric Sensor (LIS) to detect buried mines. The LIS is a laser-based electro-optic imaging technique that is utilized with an acoustic source on a VTUAV to detect buried mines. This is done by measuring the vibration of the ground above the buried mines and comparing it with the ground of the surrounding ground.

## **B. FORT WALTON ROAR EXPERIMENT**

During September and October of 2009, the Office of Naval Research conducted a experiment utilizing the ROAR sensor by Fort Walton, Florida. The experiment was conducted in the SZ and VSW regions with mission tracks parallel to the coastline. The region had a gradual sloping seafloor which is typical of the gulf coast, yet the SZ is very dynamic and complex due to foam, surface glint, waves and clutter (Almquist 2012). The survey was conducted using a Flash LIDAR imager that was mounted on a helicopter that was fling at 70 knots and an altitude of 2500ft to 3000ft.

The survey data that was used for this thesis was the 2-D LIDAR data. The horizontal area was 200 x 200 meters represented by a 1000 x 780 pixel horizontal image. The reason that the 3-D LIDAR data was not utilized was that the contrast difference between data points was very limited and only provided eight shades of grey, whereas the 2-D LIDAR data was consistently greater than 25 shades of grey.

### **1. CAD/CAC**

The goal of this research is to develop a computer-aided detection (CAD) algorithm to detect MILCOs in the SZ. Unfortunately, here has not been any research on this specific topic to date, i.e., that utilizes a CAD/CAC algorithm for a LIDAR sensor. The algorithm used in this paper was developed utilizing a method called feature extraction, which was used by the Raytheon Company (Ciany et al. 2003). This method utilized areas of highlights and areas of shadows that are geometrically associated to form regions of interest. Each point was then processed to extract key differences in the signal to noise ratios. By comparing regions with low contrasts or shadows to areas of increased brightness the algorithm was able to distinguish between background noise and MILCOs. This algorithm also utilized the 20 images of MILCOs that was provided by BAE as a

reference to what was mine like and what was not. Also, the BAE images were used to test the algorithm and to refine the search criteria to minimize false alarms.

## VI. METHODOLOGY

### A. BACKGROUND

The first step that was taken for this work getting the images from the mine shapes from the analysts from BAE. Utilizing the images of the mine shapes, work could be commenced into sorting out how to systematically break down the imagery. The area that the imagery was taken from was a sandy beach which was relatively flat and with almost no clutter or large rocks in the SZ or CLZ. This helped a lot in the analysis because it allowed many assumptions to be made. Evaluating the imagery was similar to looking for someone wearing a black jacket in a field of snow, there was not much clutter, roughness, or burial that had to be considered into the equation. The mine shapes were mostly circular in nature (that were found by the BAE analysts) except for a few hedgehog obstructions. The method to locate these mine like objects (MLOs) was broken into 7 sequential steps. The algorithm starts with the image saved from the BAE browser (Figure 13). One of the main factors that played into developing this algorithm was to make it simple yet powerful enough to locate the MLOs without a high false alarm rate. The MATLAB code used for this thesis is located in Appendix A.

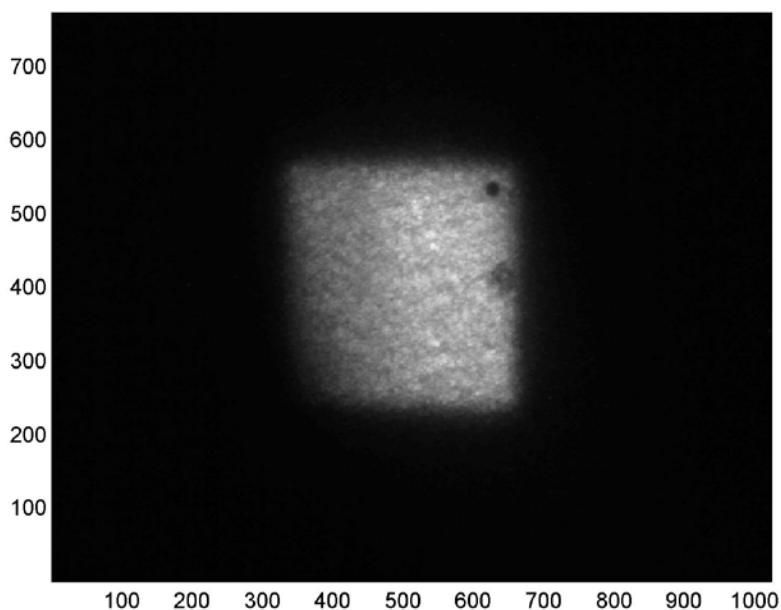


Figure 13. The initial imagery of a MLO

## B. 7 STEPS

### 1. Step 1 Reduce the Search Area

The first step, once the image was taken out of the BAE browser was to reduce the size of the image to only the relevant/usable imagery. The raw image started off having a large border that went all around the usable area that needed to be removed. Next, many of the images had up to half of the un-bordered image that was dark; again these sections were taken out. The resulting area of the usable image was a rectangular area that was carried onto into the second step.

There were two reasons for first removing the bad sections and the border. First, was so that the computational time would not be wasted analyzing sections of unusable data. Second, was to not have the contrast values skewed in later steps. This was done by quickly analyzing the data on the x and y axis and if the mean value was less than four percent (very dark) the area would be removed (Figure 14).

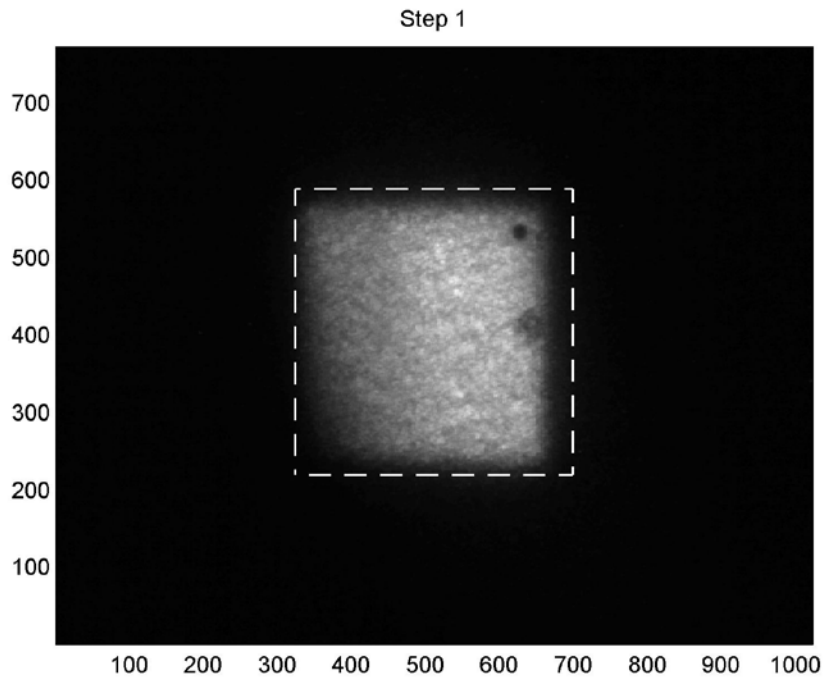


Figure 14. Step reducing the search area

## 2. Step 2 Reduce the Search Points

The area from step one was significantly reduced from the initial image but, still there were large areas in the data that could not have a MILCO in them. Large sections of the raw data were very saturated or very bright and the MILCOs were all very dark. The points that were greater than the mean brightness value for the image were removed as well. The data that was kept and moved on to step 5 was the red portion in Figure 15.

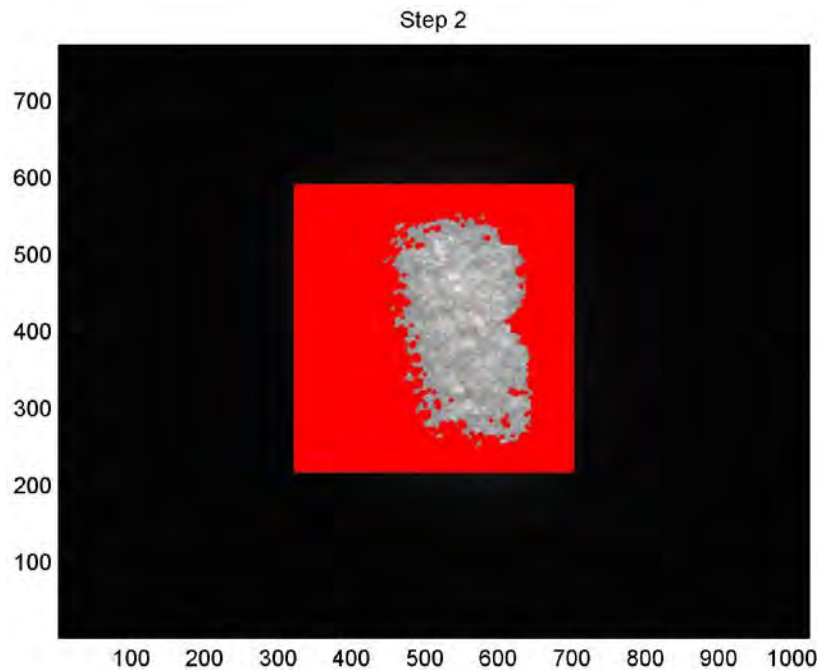


Figure 15. Removes areas with large brightness values

## 3. Step 3 Calculate the Mean Darkness Value (Rate) within 0.5R Disk

At each point, a disk that is half the radius of the mine being searched for will be analyzed. Each point of raw data from step two will now have a circle around it. The disks will then be analyzed and the mean darkness or rate of the disk will be recorded. Next, the mean darkness values will be sorted from lowest to highest and moved onto step 4.

#### 4. Step 4 Darkness at Center

The MILCO must have the disks minimum rate in the center. This step was put in because often times many points whose rate met the criteria were overlapping. This step analyzes the overlapping points and only the point whose darkest area was in the center is sent to the next step as possibly being a MILCO. This is done by comparing the rate of each circle around a point and if the darkest region is not at the center of the disk the contact is no longer kept. This step is very useful because it not only reduces the amount of overlapping points, but it also eliminates points that are relatively dark, but not dark in the center (Figure 16). If a contact is not dark in the center it was found that it did not correlate with the found MILCOs from the BAE analysts.

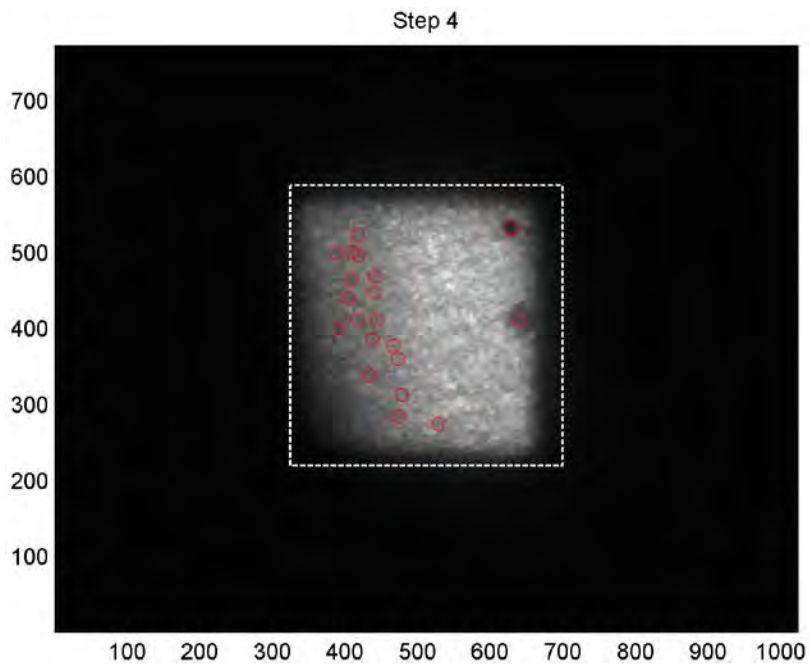


Figure 16. Object must be greater than .2 of the mean darkness value

#### 5. Step 5 Calculate the Mean Value of the Ring

In this step the points that have been moved on from step 4 are used to make a ring 1.5 to 2 times the radius of the target mine. The mean brightness value is calculated and is called the mean ring value. The value of the ring should be much brighter than that

of the disk which is dark. The mean rings value is compared to the mean disk value to get a relative darkness value or rate value using the following equation:

$$rate = \frac{mean_{ring} - mean_{disk}}{mean_{disk}}$$

The last part of this step is sorting the rate values from lowest to highest.

#### **6. Step 6 Rate >= 0.2**

This step removes the points with low relative darkness and has two parts that work together to further remove the points of no concern. First, if the rate from the points of step 5 are less than or equal to 0.2 were eliminated as seen in Figure 17. This was done because if the rate was low, they were indicative of noise in the data and not a MILCO. The next step was to compare the remaining points against the point directly below it in relative darkness. This part was done to find jumps in the rate values. These jumps between the rate values were called relative rate (rr). The equation for rr is:

$$rr_i = \frac{rate_i}{rate_{i-1}}$$

#### **7. Step 7 rr + drr >= 2.2**

This last step applies a criteria equation; if a contact meets the set criteria than the contact is mine like and would be considered a MILCO as seen in Figure 18. This last step is broken into three parts. First, a new variable was created called difference of relative rate (drr) whose equation is:

$$drr_i = rr_i - rr_{i-1}$$

This new variable was used to show the differences between large jumps in contrast between points. Second, the rr and drr for each point are summed together and saved as that points critical value. After much analysis a minimum critical value was determined to be 2.2 after much testing with the known contacts. If a points critical value was greater than or equal to the minimum critical value the contact was considered a MILCO. Third, the imagery of the MILCOs are exported as a jpg file for an operator to view (Figure 18) along with a text file that has the number of contacts, the rr value and drr values for each contact. The images that did not have any MILCO were not sent to the operator.

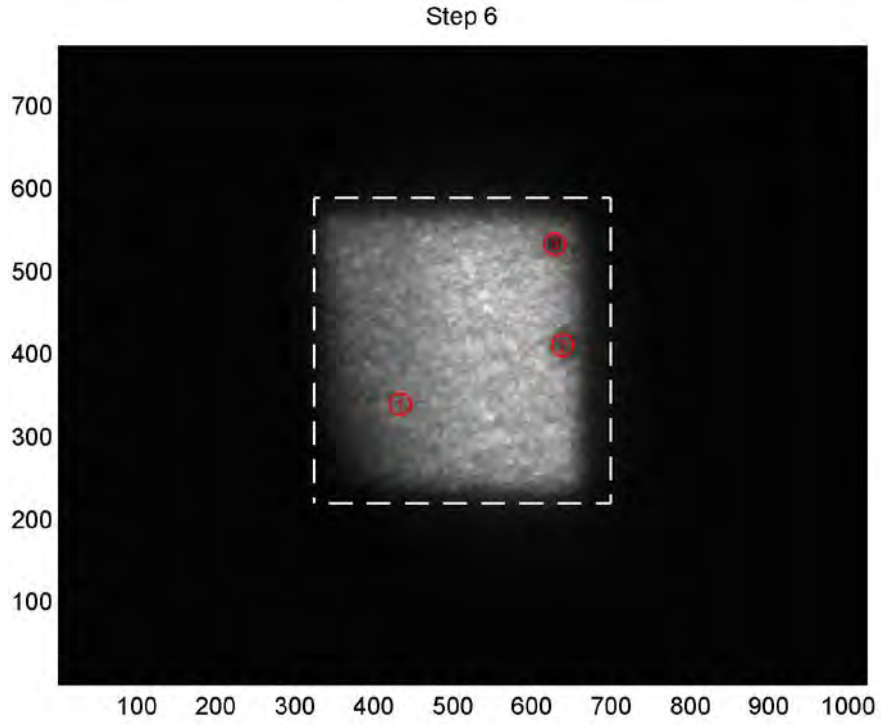


Figure 17. Reduce the points to only the largest jumps in darkness values

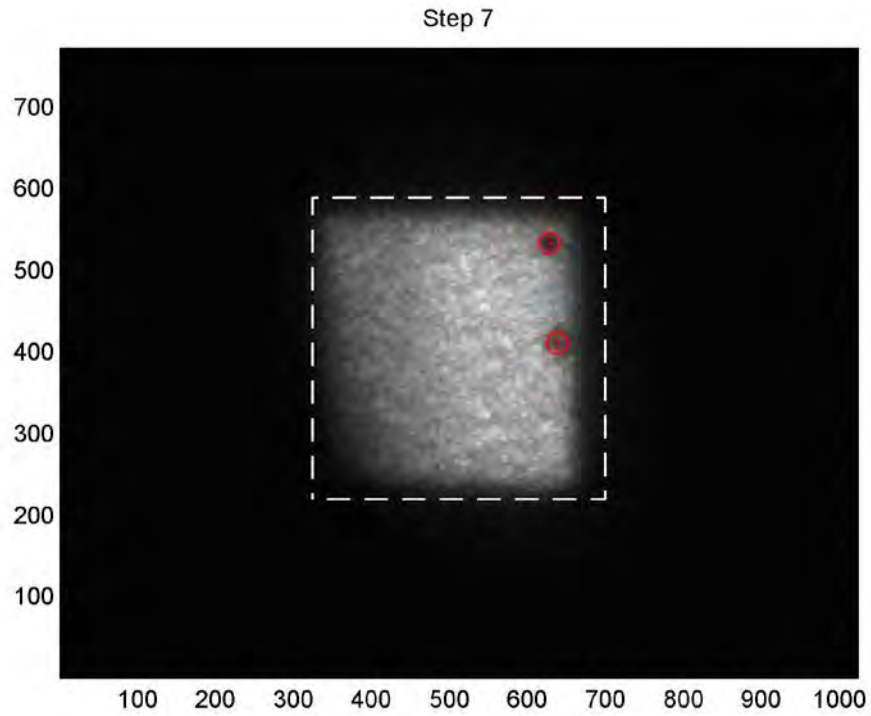


Figure 18. Apply the final search criteria to detect MILCOs

## **VII. RESULTS AND CONCLUSION**

### **A. RESULTS**

The overall results from the CAD/CAC algorithm were very positive, with all of the MILCO's from the BAE analysts being found with the algorithm. The original goal was to analyze the 3D ROAR data but the resolution was too low when exporting the imagery to remove the noise from the MILCOs. So the 2D data was used instead and the algorithm was able to locate all twenty of the contacts with out and false alarms (detecting a contact that was not a contact). The problem was that not all of the imagery was as pristine as the images where the MILCOs were detected. Also the MILCOs were not in the locations that the ground truth said they were. Overall, the algorithm performed the task that it was designed for, yet improvements in the future could be made.

The 3D ROAR data was the original goal because the imagery allowed the user to determine where in the water column the MILCO was located. Each section of data would have 44 layers with the first layer starting above the water and the last layer ending below the sea floor. This resulted in many images being unusable, but there were between four to ten images (depending on the depth of the water) of imagery through the water column. This imagery could be used to determine if a MILCO was moored which would have an image near the top to display the mine case and then in a later image the mooring or if the MILCO was a bottom mine. When going through the browser manually and viewing all the 3D imagery was very time consuming and it was very possible that a human operator could miss detecting a mine if they stopped looking at the browser for any period of time. When the raw 3D imagery was exported from the browser there were only eight shades of grey. The background noise was too high for the 7 step algorithm to distinguish a MILCO and the background. The algorithm was changed repeatedly but in order to locate the surf zone mines from the BAE analysis's the false alarm rate was such that almost every slide detected a MILCO. When looking at the exported 2D ROAR data it was found that the contrast was much better with over 50 shades of grey, and was usable for this experiment.

The BAE analysis's located 20 MILCOs in the surf zone from the experiment in 2009. The contacts fell into two categories, moored contacts and submerged contacts. The first MILCO that the BAE analyst identified was correlated well with the 7 step algorithm. The algorithm also detected the surface float that was attached to the mooring that the analysts indicated with the yellow arrow in Figure 19. This was a good example of the difference between the 2D and 3D data sets, because the 2 D image was able to show float and the mooring in one image where the 3D imagery had the float on a earlier image than the mooring. The addition of the mooring in this case was not documented as a false alarm. Overall the BAE analysts identified four moored contacts with their associated floats. The seven step algorithm located three of the four floats in the imagery and all of the moorings. The complete set of all the surf zone mine locations is found in Appendix A.

The analysis from BAE also indicated 16 subsurface MILCO's ranging from small (Figure 20) to large (Figure 21) and in some imagery there were multiple contacts (Figure 22). The Small contacts were very small on the 2D imagery and the contrast was less than 25 shades of grey. The larger contacts were much more obvious and easy to pick out. When the algorithm had to find multiple subsurface contacts in a single image is when the false alarm rate was higher. In Figure 22 the two contacts that the BAE analysts found were also found by the algorithm, but the algorithm also detected a third contact that was between the two MILCOs that appears to be a false alarm. Two of the contacts did not appear to be mines, but obstacles like a hedgehog, which is designed to damage tanks as they come ashore (Figure 23). The hedgehog has multiple straight shadow regions that resemble a star rather than a circle, but is still an obstacle that would have to be dealt with.

The false alarm rate for the imagery was very low at .09 with only two false alarms. One of the false alarms occurred when there were multiple contacts and the false alarm had an interesting shape to it but was not characteristic of the other mine shapes that were identified. The second false alarm occurred when a dark circle was on the

imagery similar to that of a MILCO. The higher the false alarm rate the more assets time that would need to be dedicated to investigate and the MILCOs which can significantly extend the MCM timelines.

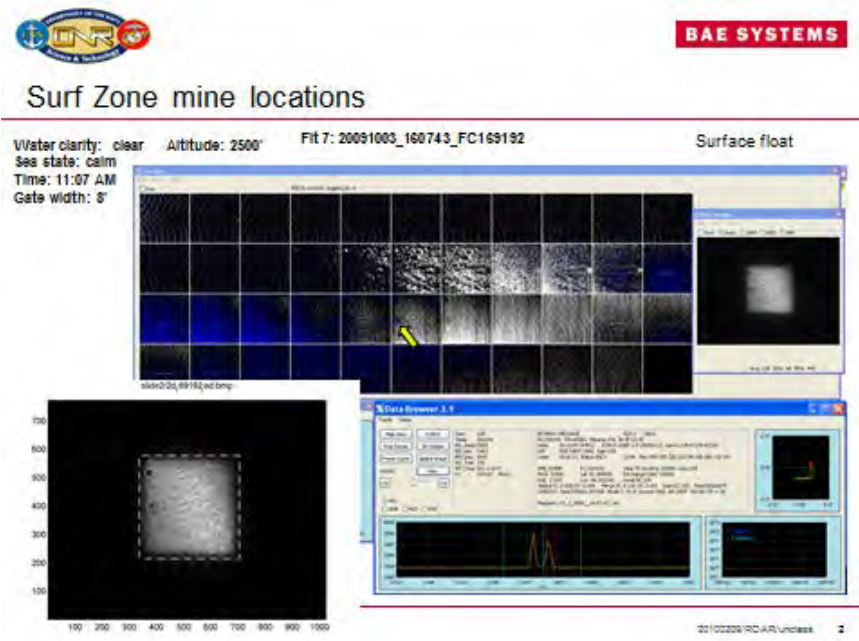


Figure 19. Moored contact from BAE with algorithm results in lower left corner



### Surf Zone mine locations

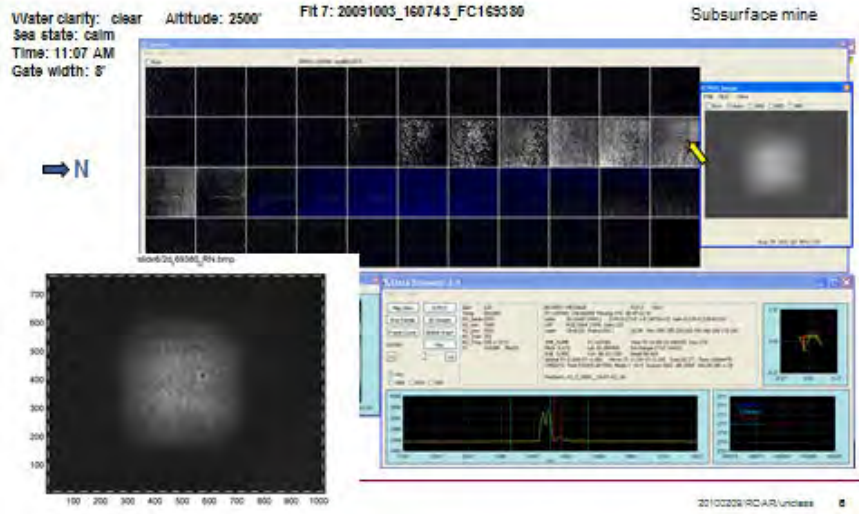


Figure 20. Small subsurface contact from BAE with algorithm results in lower left corner



### Surf Zone mine locations

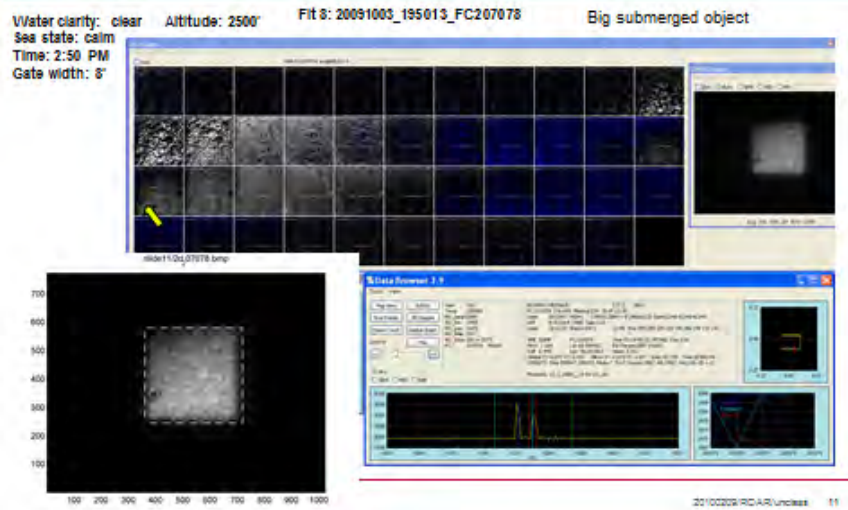


Figure 21. Large subsurface contact from BAE with algorithm results in lower left corner



### Surf Zone mine locations

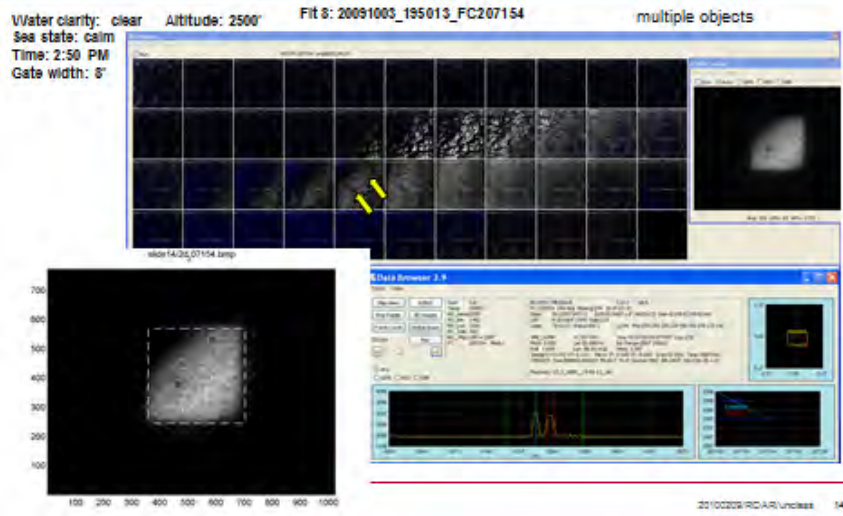


Figure 22. Multiple subsurface contact from BAE with algorithm results in lower left corner



### Surf Zone mine locations

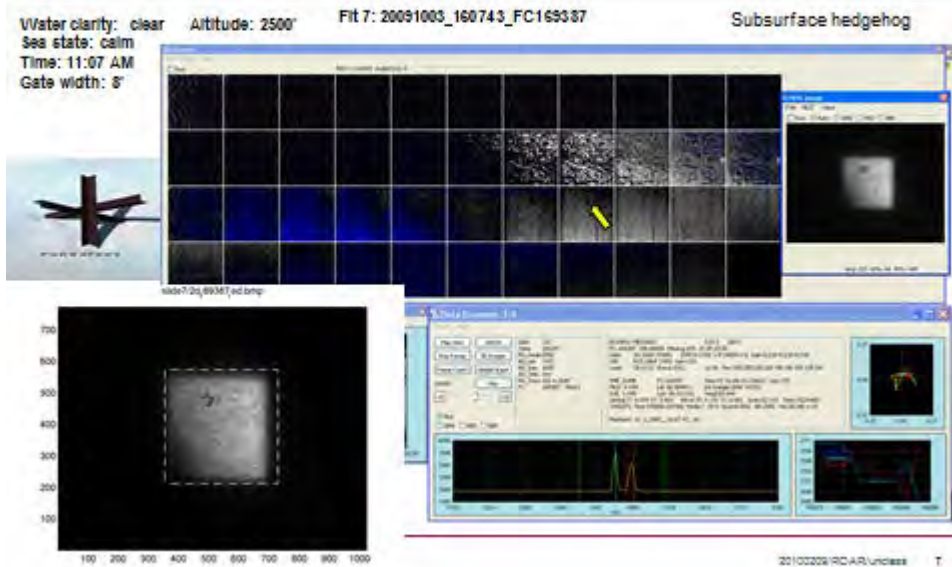


Figure 23. Hedgehog subsurface contact from BAE with algorithm results in lower left corner

In addition to the 20 images of MILCOs from BAE, an additional 100 images were randomly taken from a mission on October 3, 2009. This data set was chosen because it contained images that BAE analyzed as mine like and the track of the helicopter went directly through the surf zone mine field. The 20 images that BAE had shown had very good images and the ability to see through the water column was very clear but the majority images were not of this quality. The images were broken down into four categories: good (which were like the 20 in the BAE analysis), partial, dark, and surface.

The good images are like the ones previously seen. The partial images had some usable imagery but some there were portions that were removed (Figure 24). The dark images were images where the image was almost completely dark and contrast needed to be adjusted to view the image (Figure 25). The surf image was one in which the image exported was of the sea surface and were mostly waves (Figure 25). Of the 100 additional images that were analyzed 20 were good, 51 were partial, 10 were surface, and 19 were dark. When the imagery was not good the false alarm rate increased and possible missed calls could emerge.

The partial images made up the majority of the images that were seen in all the data sets. Also the partial images were only the partial images that did not have surface return or were very dark, but partially good imagery. The 7 step algorithm was not able to work very well in the border regions of the unusable imagery as seen in Figure 24. This problem occurred in 4 of the images and mines were detected erroneously. The overall false alarm rate in the partial images was 27.3 percent with eleven contacts called and three of which were erroneous. The dark images occurred at about the same rate as the good imagery and forced the operator to pause and adjust the contrast to view the imagery and then reset the contrast before proceeding onto the next image (Figure 25). This was very time consuming and the overall process inefficient. The 7 step algorithm called three MILCOs with only 1 being obviously incorrect, for a False alarm rate of 33.3 percent. The surface images were the least seen but the most problematic (Figure 26). The images with surface return varied in contrast immensely which acted like a high clutter and rough bottom type which this algorithm was not designed for. In the ten

images in this random sampling one of the images had a false alarm. The overall false alarm rate for the surface images was 100 percent. Overall the false alarm rate was 22.7 percent over the 100 random images.

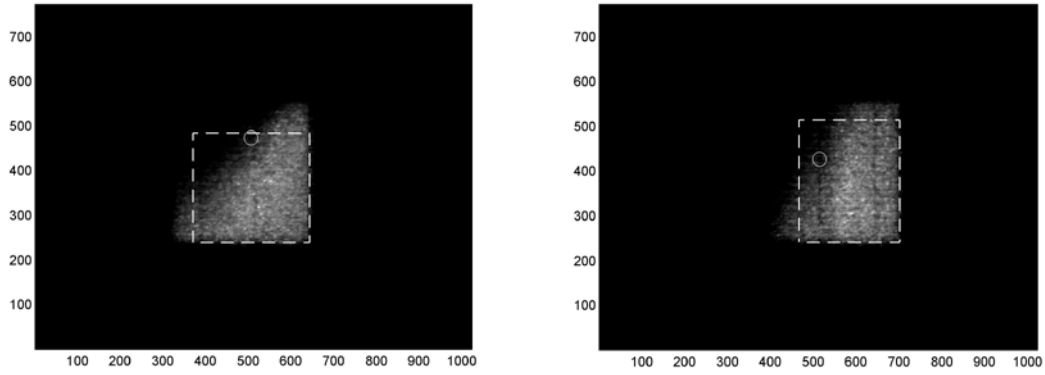


Figure 24. Images that was only partially usable

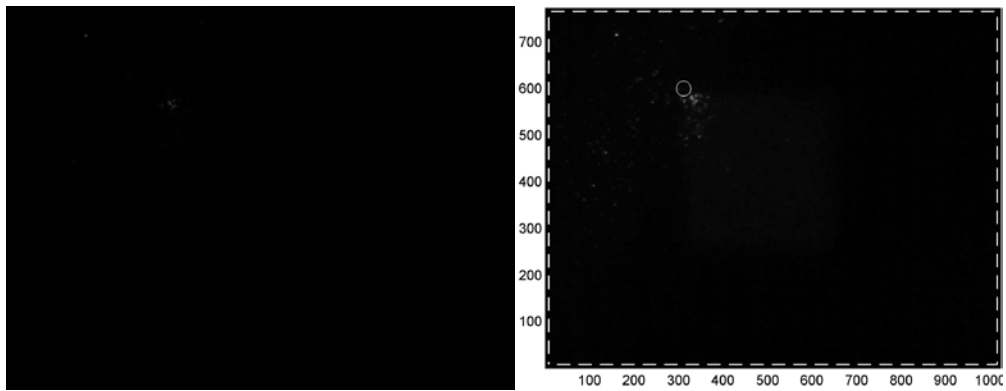


Figure 25. Images of the raw image and then after the 7 step algorithm

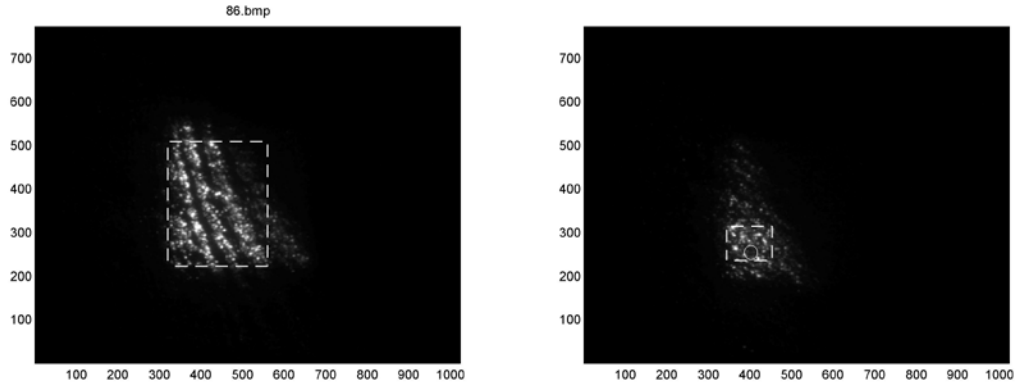


Figure 26. Images of surface return of the water

## B. CONCLUSION

This research was intended to show that a CAD/CAC program could and would be effective with the new COBRA sensor. The time needed to fully analyze the ROAR data was very tedious to the point of almost being tactically irrelevant. The 7 step algorithm was able to find the MILCO effectively in a low clutter, low roughness environment when the imagery was good. The algorithm was much faster at going through the imagery than human operator. The goal was to develop an algorithm that could detect and classify a MILCO, but the resolution was insufficient to classify the MILCOs beyond whether the MILCO was moored or a bottom contact. Lastly this research was intended to show that a CAD/CAC program was capable of finding MILCOs in the SZ and CLZ, but a more robust program is needed to handle the varying DBT environments that will be encountered.

It should be noted that when the imagery was not good the false alarm rate rose greatly and the effectiveness of the algorithm dwindled. Also this algorithm is dependent on knowing the mine size; if the mine size is unknown the effectiveness of the algorithm is unknown. The imagery georectification was off by more than 30 meters at times making it impossible to correlate the image to the ground truth.

## C. FURTHER RESEARCH

To further the research presented in this paper, a larger and more updated data would be imperative. With a newer COBRA sensor currently being developed a good

deal of the imagery problems will be corrected and resolution should be enhanced. Updating the current algorithm utilizing the updated sensor could be very beneficial.

A standalone CAD/CAC program is helpful, but having the CAD/CAC program incorporated into the actual browser would be much more effective. Developing a way to be able to plug a CAD/CAC program into the browser would be much more effective. The ability to update and allow the user to see the results of the program at the same time as they are seeing the imagery would also be very beneficial.

The latitude and longitude of all the contacts that BEA found were mine like did not correlate to the ground truth of the mine field. Developing a way to georectify the imagery so that MILCOs can be reacquired is essential to prosecuting and neutralizing threats. Utilizing the Gimbal information, altitude, along with the latitude and longitude could provide a way to better truly locate mines and obstacles.

THIS PAGE INTENTIONALLY LEFT BLANK

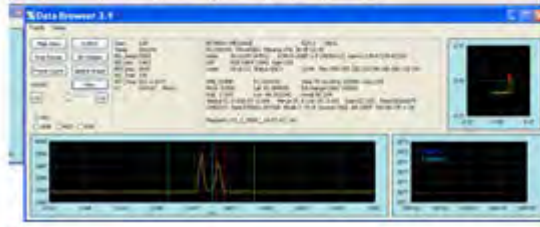
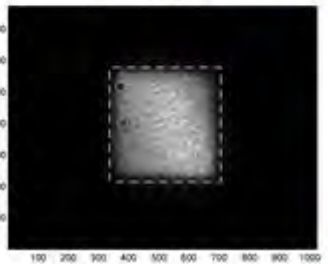
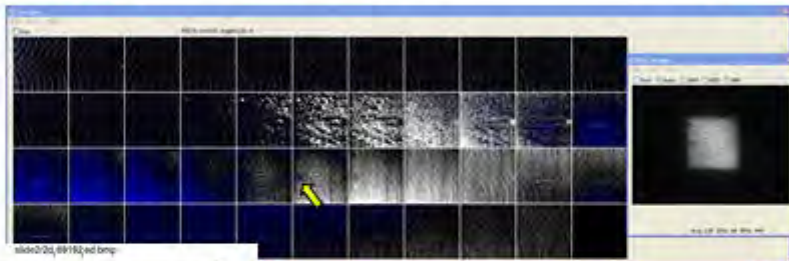
# APPENDIX A. SURF MINE LOCATIONS



BAE SYSTEMS

## Surf Zone mine locations

Water clarity: clear    Altitude: 2500'    Fit 7: 20091005\_160743\_FC169192    Surface float  
Sea state: calm  
Time: 11:07 AM  
Gate width: 8'



20100202/RCAR/Unclss 2

1

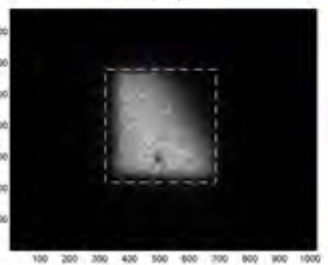
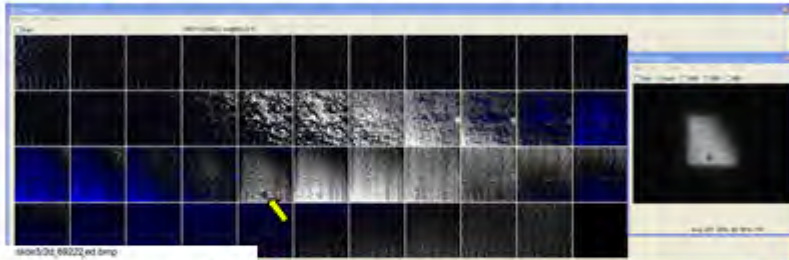


BAE SYSTEMS

## Surf Zone mine locations

Water clarity: clear    Altitude: 2500'    Fit 7: 20091005\_160743\_FC169222    Moored equipment on bottom  
Sea state: calm  
Time: 11:07 AM  
Gate width: 8'

→ N



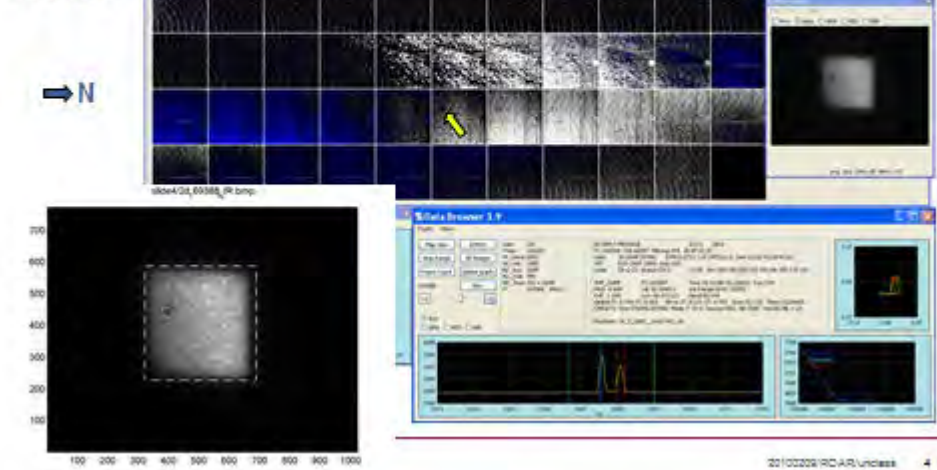
20100202/RCAR/Unclss 2

2



### Surf Zone mine locations

Water clarity: clear    Altitude: 2500'    Fit 7: 20091003\_160743\_FC169388    Subsurface object

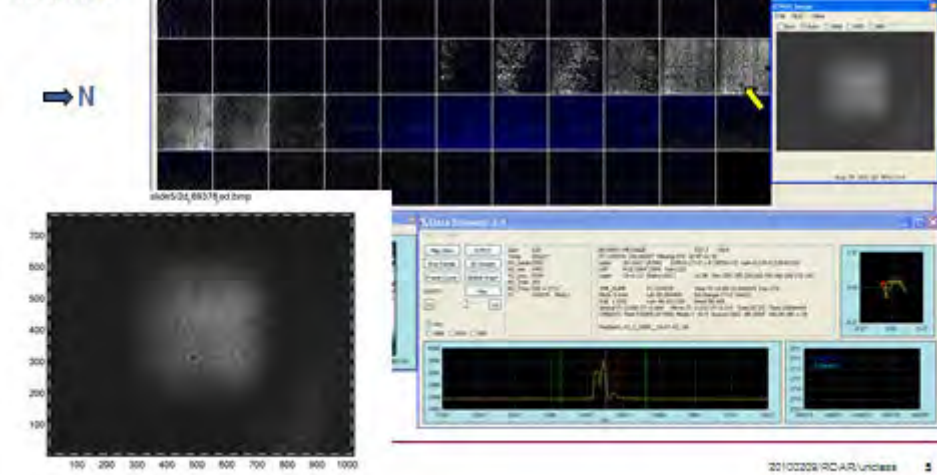


3



### Surf Zone mine locations

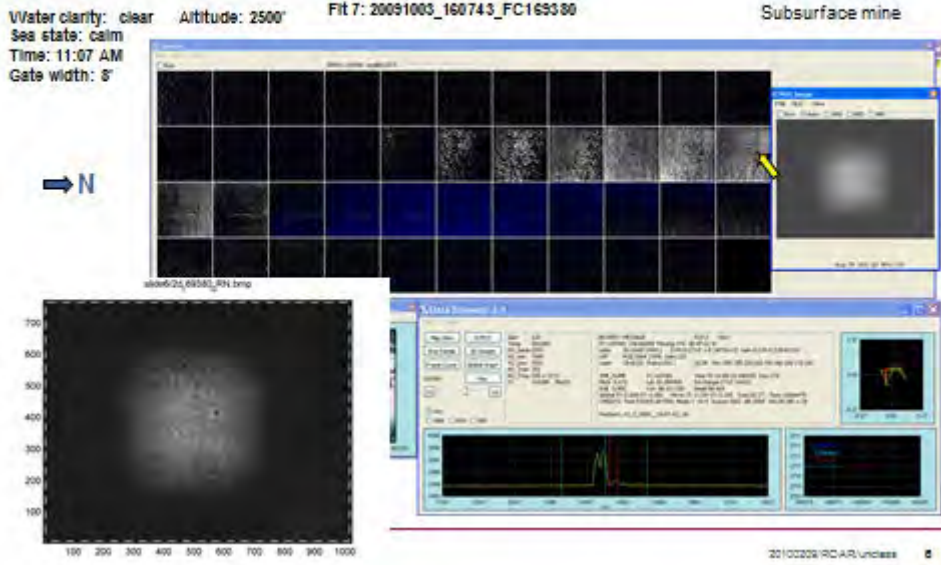
Water clarity: clear    Altitude: 2500'    Fit 7: 20091003\_160743\_FC169378    Subsurface mine



4



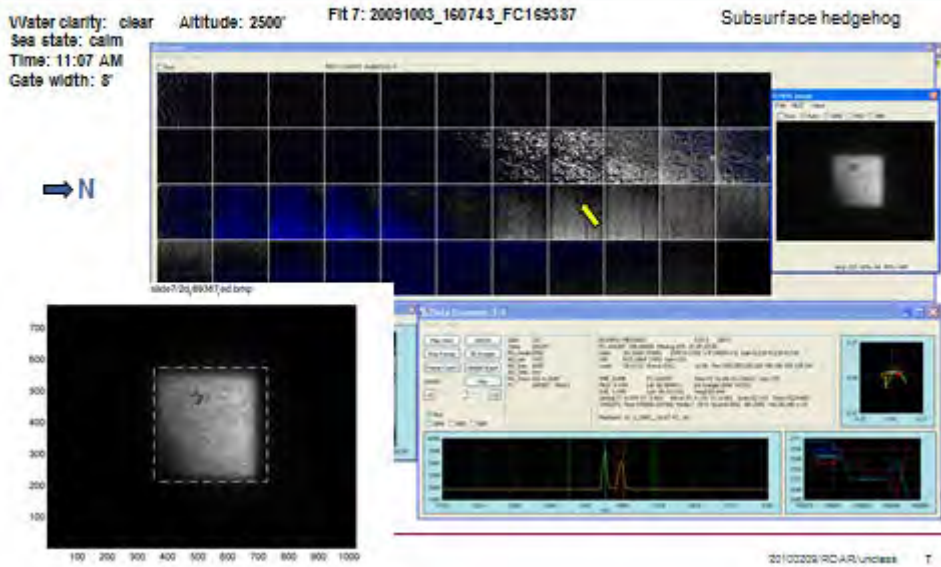
### Surf Zone mine locations



5



### Surf Zone mine locations

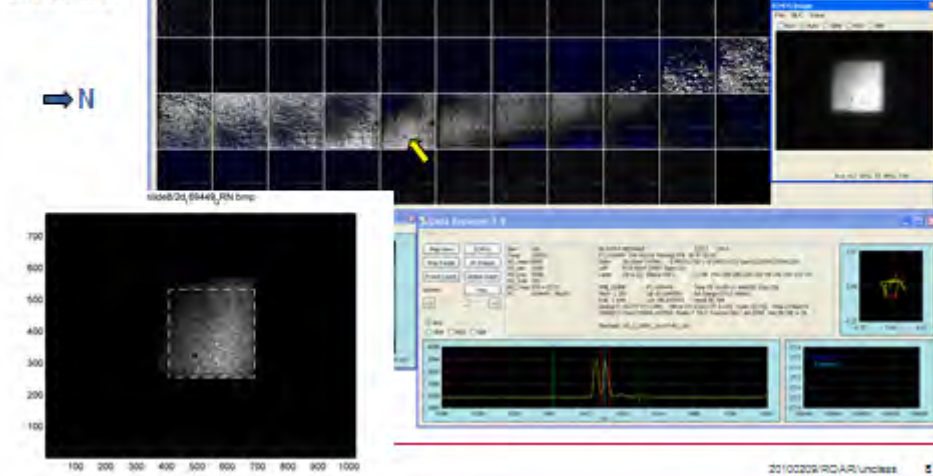


6



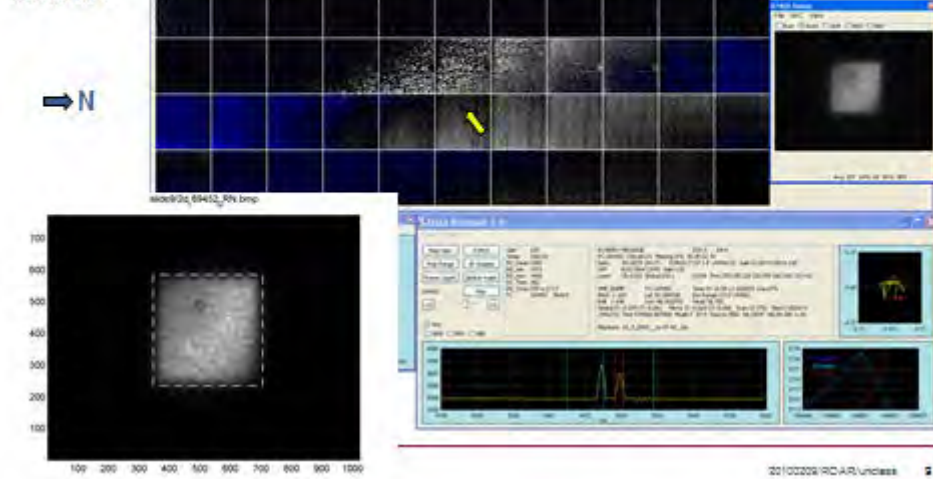
### Surf Zone mine locations

Water clarity: clear    Altitude: 2500'    Fit 7: 20091003\_160743\_FC163449    Surface float and subsurface mine



### Surf Zone mine locations

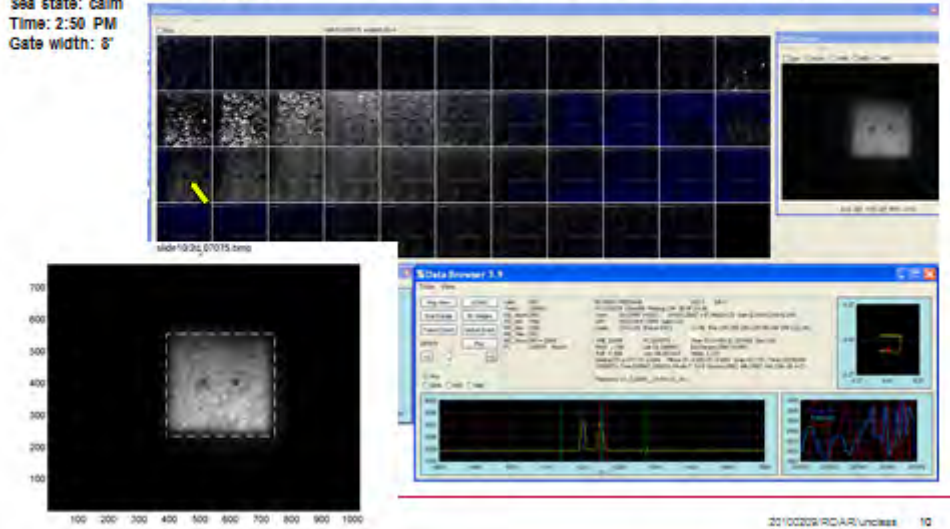
Water clarity: clear    Altitude: 2500'    Fit 7: 20091003\_160743\_FC163452    Subsurface object





### Surf Zone mine locations

Water clarity: clear    Altitude: 2500'    Fit #: 20091003\_195013\_FC207075    Float + submerged object  
Sea state: calm  
Time: 2:50 PM  
Gate width: 8'

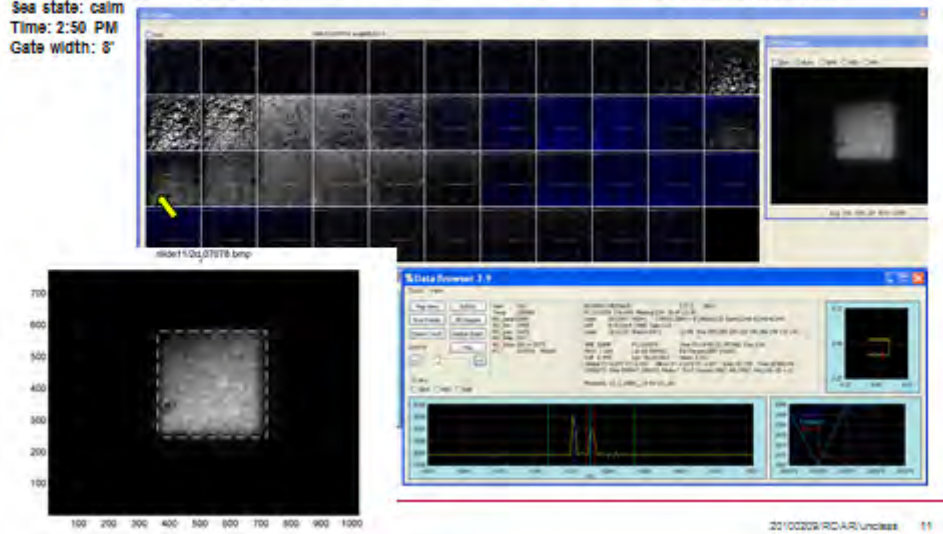


9



### Surf Zone mine locations

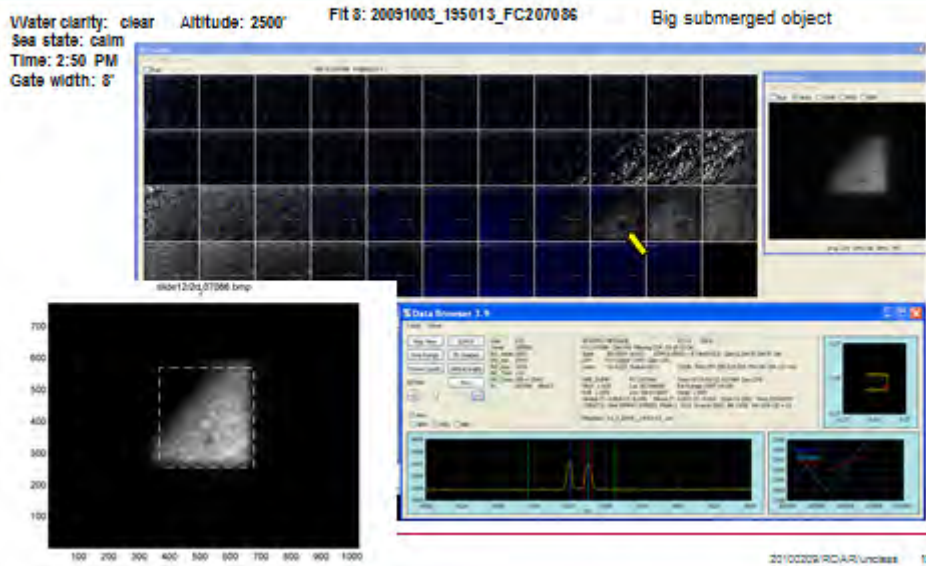
Water clarity: clear    Altitude: 2500'    Fit #: 20091003\_195013\_FC207078    Big submerged object  
Sea state: calm  
Time: 2:50 PM  
Gate width: 8'



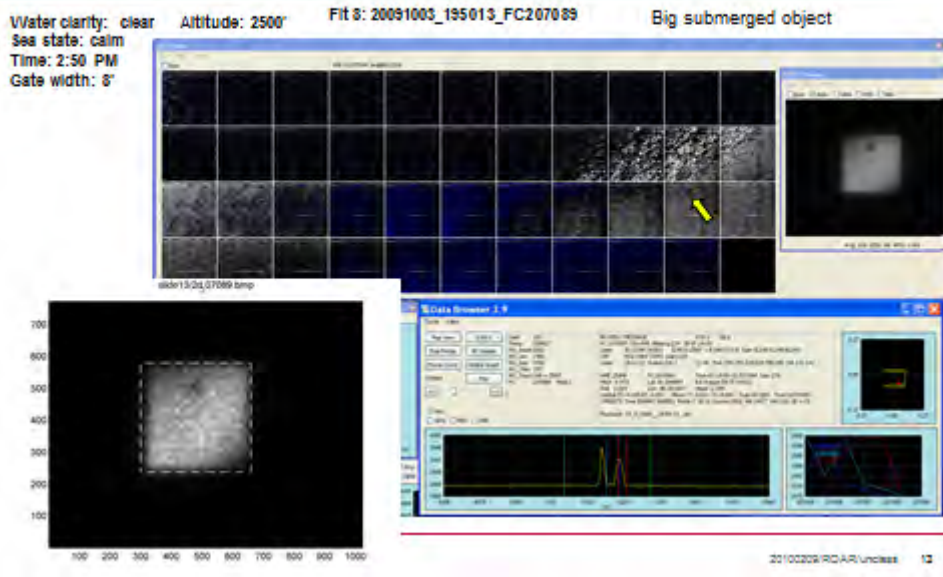
10



### Surf Zone mine locations

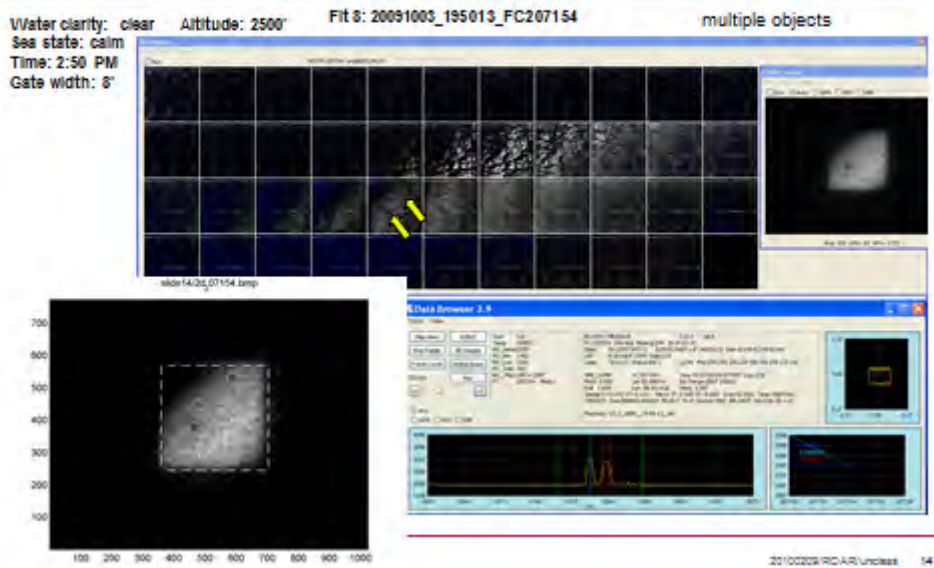


### Surf Zone mine locations





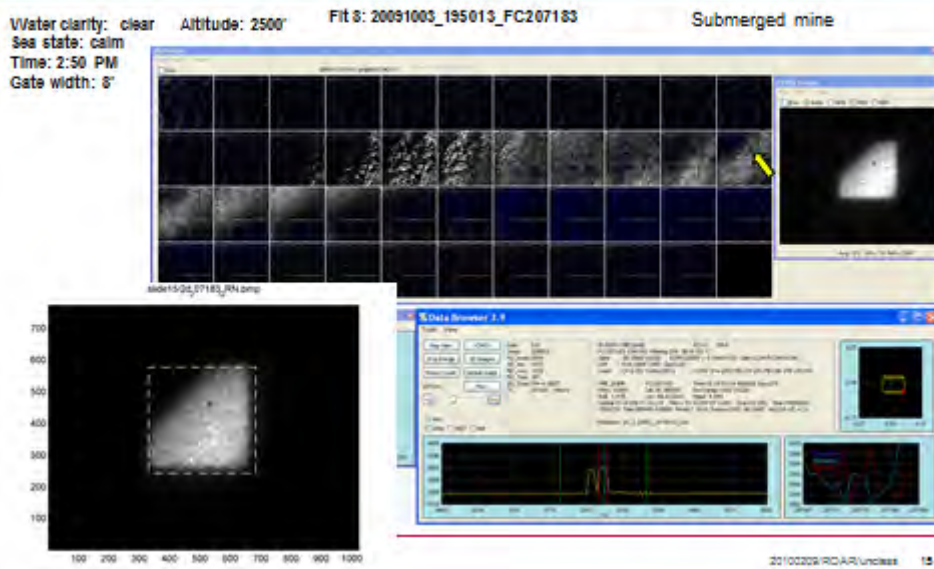
### Surf Zone mine locations



13



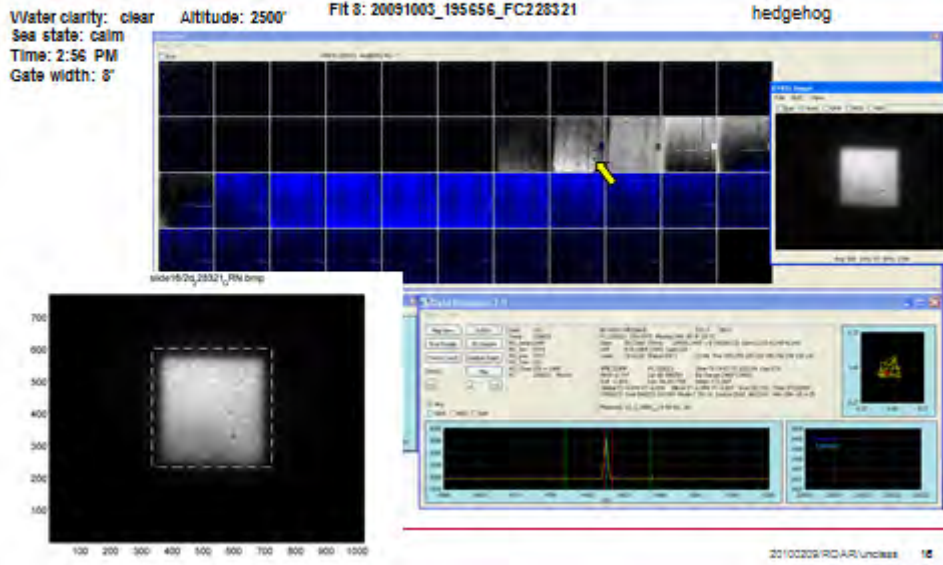
### Surf Zone mine locations



14



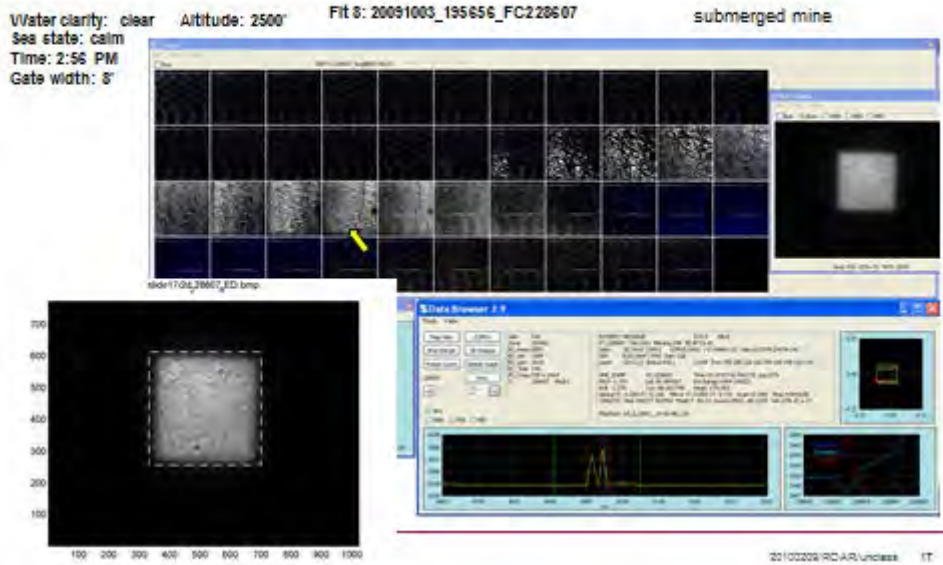
### Surf Zone mine locations



15



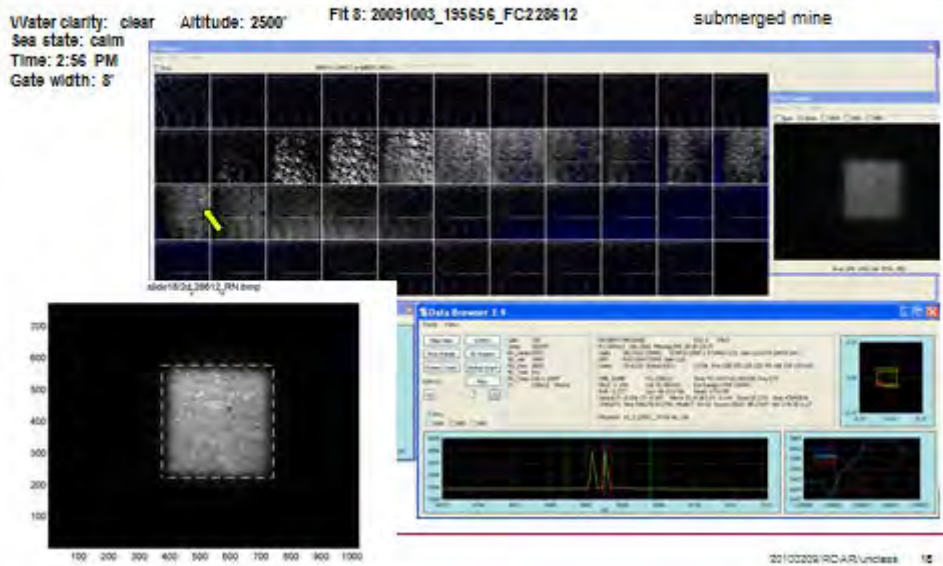
### Surf Zone mine locations



16



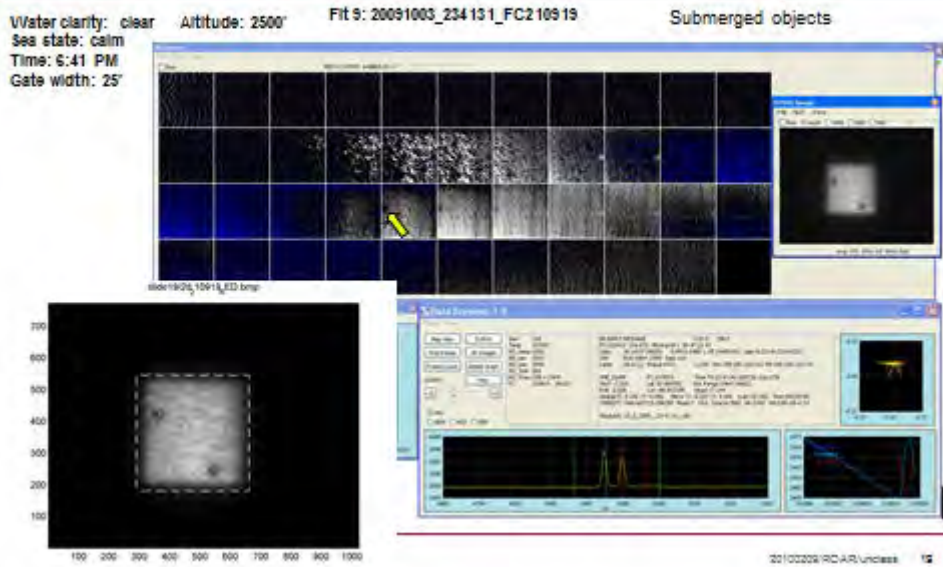
### Surf Zone mine locations



17



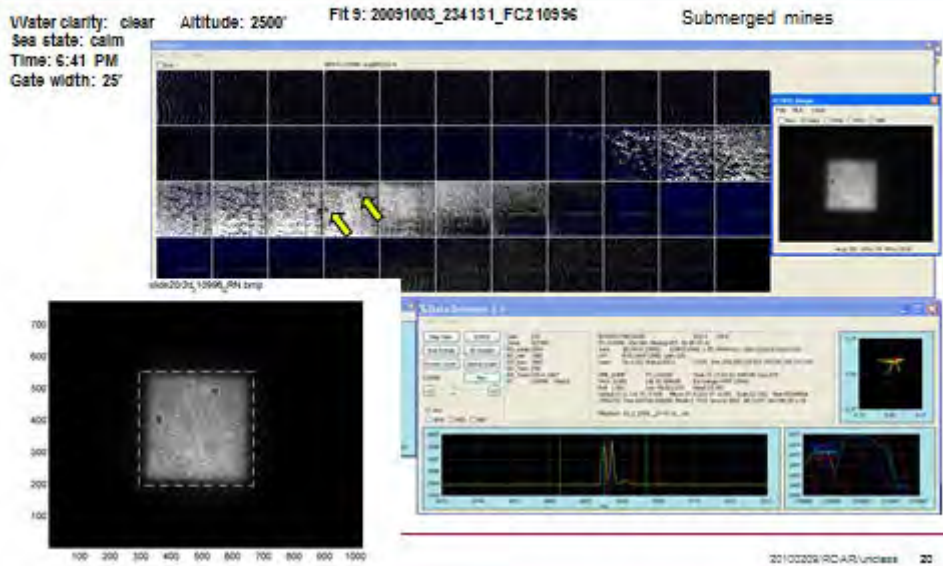
### Surf Zone mine locations



18



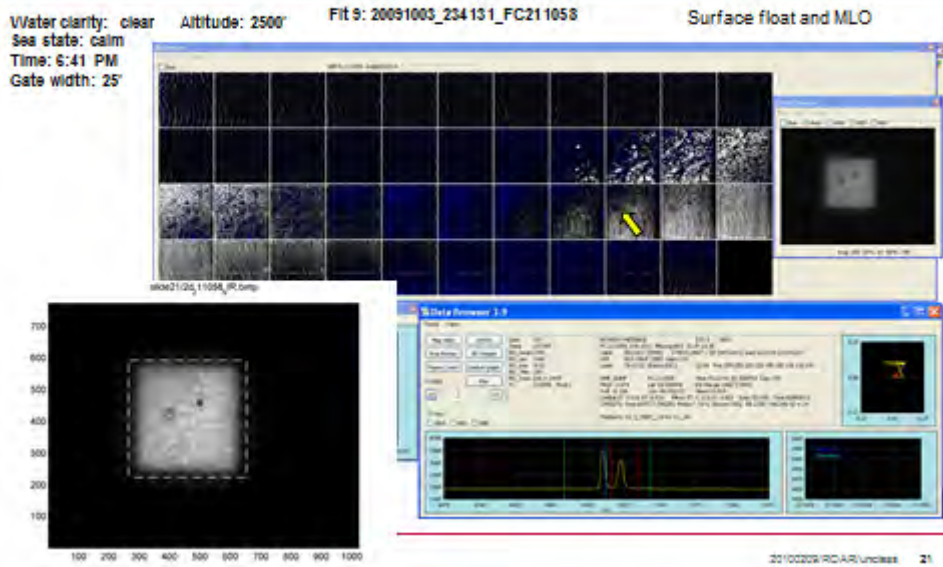
### Surf Zone mine locations



19



### Surf Zone mine locations



20

## APPENDIX B MATLAB CODE

### A. FIND MINE

```
clear;

% drs={'slide2//','slide2//','slide3//',...
%      'slide4//','slide5//','slide6//',...
%      'slide7//','slide7//','slide8//',...
%      'slide9//','slide10//','slide11//',...
%      'slide12//','slide13//','slide14//',...
%      'slide15//','slide16//','slide17//',...
%      'slide18//','slide19//','slide20//',...
%      'slide21//'};
% fnm={'2d_169192_red.bmp','2d_169193_NIR.bmp','2d_169222_red.bmp',...
%      '2d_169388_NIR.bmp','2d_169378_red.bmp','2d_169380_GRN.bmp',...
%      '2d_169386_GRN.bmp','2d_169387_red.bmp','2d_169449_GRN.bmp',...
%      '2d_169452_GRN.bmp','2d_207075.bmp','2d_207078.bmp',...
%      '2d_207086.bmp','2d_207089.bmp','2d_207154.bmp',...
%      '2d_207183_GRN.bmp','2d_228321_GRN.bmp','2d_228607_RED.bmp',...
%      '2d_228612_GRN.bmp','2d_210919_RED.bmp','2d_210996_GRN.bmp',...
%      '2d_211058_NIR.bmp'};
% OSZ=[16,14,16,...
%      16,16,16,...
%      16,16,16,...
%      16,16,16,...
%      16,16,16,...
%      16,16,16,...
%      16,16,16,...
%      16];
fid=fopen('checknew.txt','w+');
fprintf(fid,'p2=0.5, Critdrr=2.2\n');
for k=1:100
    filename=[int2str(k),'.bmp'];
    data=double(imread(filename));

    data=flipud(data);

    Obj=identifyObjnew(data,16,1);

    if ~isempty(Obj)
        eval(['ObjV',int2str(k),'=ObjV;']);

        svinsert([filename(1:end-4),'new'],4);

        % check
        tt=ObjV(:,3:4);
        ss=['k=',int2str(k),' ',filename,' Obj
number=',int2str(size(Obj,1))];
        disp(ss);
        disp(tt);
        fprintf(fid,'%s\n',ss);
    end
end
```

```

        fprintf(fid, '%10.4f %10.4f\n', tt');
    end
end
fclose(fid);

```

## B. FIND OBJECT

```

function Obj = identifyObjnew(data,R,plt,maxObj)
% function Obj = identifyObjnew(data,R,plt,maxObj);
% must input:
% data: 2-D data
% R: the radius of objector (index)
% plt: image plot key ( 1-plot 0-no plot )
% maxObj: maximum number of Objector (default: 3)

ngin=nargin;
if(ngin < 2), error('Not enough input arguments. '); end

if ~exist('plt','var'), plt=0; maxObj=3; end
if ~exist('maxObj','var'), maxObj=3; end

p2=0.5; Critdrr=2.2; Obj=[];

%          ----- STEP 1: reduce the search area -----
%
% Many data files have large areas in which the data is not
usable.
% Reducing the area in which MATLAB needs to analyze reduces
% processsing time and therefore war fighter timelines.
% x (y) mean value < 4% (dark) will not be the search area

tclin=min(data(:))+(max(data(:))-min(data(:)))*0.04;

Hr=0.5*R;          % calculate area radius.
IR2=floor(2*R); IHr=floor(Hr);
[My,Mx]=size(data);
if(plt)
    xl=0.02; xd=0.48; xdd=xd+0.01;
    yl=0.01; yd=0.3; ydd=yd+0.03;
    figure('units','inches','position',[2,2,7,8]);
    axes('position',[xl,yl+2*ydd,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
        'xtick',[],'ytick',[],'fontsize',8); hold on;
    pcolor(data); shading flat; hold on;
    colormap('gray');
    title('Original Data'); drawnow;
end

I1=1+IHr; I2=Mx-IHr; J1=1+IHr; J2=My-IHr;
[XX,YY]=meshgrid(1:Mx,1:My);

xmean=mean(data); ymean=mean(data,2);
ii=find(xmean>tclin); I1=max(I1,ii(1)); I2=min(I2,ii(end));
ii=find(ymean>tclin); J1=max(J1,ii(1)); J2=min(J2,ii(end));

```

```

if(plt)

axes('position',[xl+xdd,y1+2*ydd,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
    'xtick',[],'ytick',[],'fontsize',8); hold on;
pcolor(data); shading flat; hold on;
colormap('gray');
plot([I1,I2,I2,I1,I1],[J1,J1,J2,J2,J1],'w--','linewidth',1);
title('Step1: reduce the search area '); drawnow;
end

[X,Y]=meshgrid(I1:I2,J1:J2);

data1=data(J1:J2,I1:I2);
darkref=prctile(data1(:),95)-prctile(data(:),5);
Tmax=max(data1(:)); Tmini=min(data1(:));

% ----- Step2: Reduce the search points as only consider <50% -----
%
% The raw data has areas in which the sensor has become saturated
and
% the data is not usable.
% reducing the area further to remove the saturated data regions
% further reduces processing time.
% Only consider the points less than the middle brightness
% (dark critical value)

pct2=Tmini+(Tmax-Tmini)*p2;

JI12=My*(X(:)-1)+Y(:); JI12=JI12';
JI12=JI12(data(JI12)<pct2);
M=length(JI12);

if(plt)
axes('position',[xl,y1+ydd,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
    'xtick',[],'ytick',[],'fontsize',8); hold on;
pcolor(data); shading flat; hold on;
colormap('gray');
plot([I1,I2,I2,I1,I1],[J1,J1,J2,J2,J1],'w--','linewidth',1);
plot(XX(JI12),YY(JI12),'r.');
```

```

title('Step2: Reduce the search points'); drawnow;
end

%----- Step3: Calculate the mean value within 0.5R disk -----
% the relative index within 0.5R disk.
% calculate the mean darkness value of half the radius of the
given
% mine that is to be search for
r=Hr;

[Xr,Yr]=meshgrid(-Ihr:Ihr,-Ihr:Ihr); % sub region
ii=find(Xr.^2+Yr.^2<=r^2);

```

```

ji_disk=My*Xr(ii)+Yr(ii);           % relative disk global index
N=length(ji_disk);

% Calculate the mean value within 0.5R disk
Midx=round((0:0.05:1)*M);
Msub=diff(Midx);
meanji=[];
for k=1:20
    JI=ones(N,1)*JI12(Midx(k)+1:Midx(k+1))+ji_disk*ones(1,Msub(k));
    meanji=cat(2,meanji,mean(data(JI)));
end

% build disk mean value filed as data2 to determine the possible
objector
data2=data; data2(JI12)=meanji;

%--- Step4: The objector must be: minimum disk mean value at the disk
center
% (dark). ---
% When multiple dark area are overlapping, only the darkest
(center)
% is kept for future evaluation.
ji0=[]; mean_disk=[];
for k=1:20
    JI=ones(N,1)*JI12(Midx(k)+1:Midx(k+1))+ji_disk*ones(1,Msub(k));
    [Tmin,j0]=min(data2(JI));
    i0=find(j0==(N+1)/2 & Tmin>0.05*Tmax);
    ji0=cat(2,ji0,JI12(i0+Midx(k)));
mean_disk=cat(2,mean_disk,Tmin(i0));
end
i0=ceil(ji0/My); j0=ji0-My*(i0-1);
mean_disk=mean_disk';

if(plt)
axes('position',[xl+xdd,yl+ydd,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
'xtick',[],'ytick',[],'fontsize',8); hold on;
pcolor(data); shading flat; hold on;
colormap('gray');
plot([I1,I2,I2,I1,I1],[J1,J1,J2,J2,J1],'w--','linewidth',1);
plot(XX(ji0),YY(ji0),'ro');
title('Step4: Darkness at center'); drawnow;
end

if isempty(ji0), return; end

% -- Step5: Calculate the mean value of the ring (1.5R <= r <= 2R), --
% and sort the rate
% (relative difference value = (mean_ring-mean_disk)/mean_disk).
% The dark disks from step 4 is taken and then a ring is calculated
% around the dark region that is between 1.5 and 2 times the radius
of the
% objector (Mine). This new ring should be much brighter than the
dark

```

```

%   disk that it is encircling. Calculates the relative darkness
%   difference between the out ring the dark disk in the center.
Lastly
%   sorts the relative darknes values from lowest to highest.

[Xr,Yr]=meshgrid(-IR2:IR2,-IR2:IR2);           % sub region
XYr=sqrt(Xr.^2+Yr.^2);
ii=find(XYr>=1.5*R & XYr<=2*R);
i_ring=Xr(ii); j_ring=Yr(ii);
ji_ring=My*Xr(ii)+Yr(ii);                       % relative global ring
index
N=length(ji_ring);

M=length(ji0);
Midx=round((0:0.05:1)*M);
Msub=diff(Midx);
mean_ring=[];
for k=1:20
    meanring=NaN*ones(1,Msub(k));
    JI=ones(N,1)*ji0(Midx(k)+1:Midx(k+1))+ji_ring*ones(1,Msub(k));
    I=ones(N,1)*i0(Midx(k)+1:Midx(k+1))+i_ring*ones(1,Msub(k));
    J=ones(N,1)*j0(Midx(k)+1:Midx(k+1))+j_ring*ones(1,Msub(k));
    minI=min(I); maxI=max(I); minJ=min(J); maxJ=max(J);
    ii= minI>=1 & maxI<=Mx & minJ>=1 & maxJ<=My;
    if sum(ii)>0
        meanring(ii)=mean(data(JI(:,ii)));
    end
    ii= minI<1 | maxI>Mx | minJ<1 | maxJ>My;
    if sum(ii)>0
        ii=find(ii>0);
        for j=1:length(ii)
            i=ii(j);
            jj= I(:,i)>=1 & I(:,i)<=Mx & J(:,i)>=1 & J(:,i)<=My;
            meanring(i)=mean(data(JI(jj,i)));
        end
    end
    mean_ring=cat(2,mean_ring,meanring);
end
mean_ring=mean_ring';
meandisk=mean_disk;
meandisk(meandisk<1)=1;
Rate=(mean_ring-mean_disk)./meandisk;
%Rate=(mean_ring-mean_disk)./darkref;

[Rate,idx]=sort(Rate); mean_ring=mean_ring(idx);
i0=i0(idx); j0=j0(idx); mean_disk=mean_disk(idx);

%--- Step6: only consider rate>=0.2 then cut the data to
%           the maximum objector number on highest rate.
%           Any thing less than 20 percent relative darknes is not
%           considered for future steps. Compare the relative darkness
values
%           to the relative darkness value directly behind each
%           value. By doing this you can tell which relative darkness
%           point stands out from the rest.

```

```

Len=length(Rate);
ist=max(1,Len-maxObj);
ii=find(Rate<0.2);
if(~isempty(ii)), ist=max(ist,ii(end)); end
if ist>1, rr0=max(1,Rate(ist)/Rate(ist-1)); else rr0=1; end
iidx=ist:Len;
i0=i0(iidx); j0=j0(iidx); mean_disk=mean_disk(iidx);
Rate=Rate(iidx); mean_ring=mean_ring(iidx);

if(plt)
    axes('position',[xl,y1,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
        'xtick',[],'ytick',[],'fontsize',8); hold on;
    pcolor(data); shading flat; hold on;
    colormap('gray');
    plot([I1,I2,I2,I1,I1],[J1,J1,J2,J2,J1],'w--','linewidth',1);
    ji0=My*(i0-1)+j0;
    H=plot(XX(ji0),YY(ji0),'ro','markersize',9);
    for k=1:length(i0)
H=cat(1,H,text(i0(k),j0(k),1,int2str(k),'HorizontalAlignment',...
        'center','fontsize',6,'color','r'));
    end
    title('Step6: Rate>=0.2'); drawnow;
end

%--- Step7: Find Relative rate + difference of Relative rate >
Critrr(2.2)
%
% The take the relative darkness values with the largest jump
% between. This value is called Critical darknes number.
There
%
% are two criteria that must bet met to call an object a
MILCO.
%
% For high resolution data(>25 shades of grey) the relative
% darknes must be greater than or equal to the Critical
% darknes(CritRT)
%
% and have a jump in relative darknes greater than Critical
jump (Crt)

% if(Tmax>25) % high resolution data
% Crt1=1.5; Crt2=1.25;
% else % low resolution data
% Crt1=1.35; Crt2=1.2;
% end

if length(Rate)==1
    if Rate>0.5
        Obj=[i0(end),j0(end)]; rr=1;
    end
else
    rr=cat(1,rr0,Rate(2:end)./abs(Rate(1:end-1)));
    drr=cat(1,0,diff(rr));

```

```

        ii=find(rr+drr>=Critdrr);
        ii=ii(1):length(i0);
        if ~isempty(ii)
            ii=ii(1):length(i0);
            Obj=[i0(ii)',j0(ii)'];
        end
    end
end

if isempty(Obj), return; end

V=[mean_disk,mean_ring,rr,drr];
assignin('base','ObjV',V);
if(plt)
    disp(['Tmax=',num2str(Tmax)]);
    axes('position',[xl+xdd,y1,xd,yd],'xlim',[1,Mx],'ylim',[1,My],...
        'xtick',[],'ytick',[],'fontsize',8); hold on;
    pcolor(data); shading flat; hold on;
    colormap('gray');
    plot([I1,I2,I2,I1,I1],[J1,J1,J2,J2,J1],'w--','linewidth',1);
    ji0=My*(i0-1)+j0;
    H=plot(XX(ji0(ii)),YY(ji0(ii)),'ro','markersize',9);
    for k=1:length(ii)
        H=cat(1,H,text(i0(ii(k)),j0(ii(k)),1,int2str(ii(k)),'HorizontalAlignmen
t',...
            'center','fontsize',6,'color','r'));
    end
    title('Step7: rr+drr>2.2'); drawnow;

end

if plt & ~isempty(Obj)
    xx=R*cos((0:80)*pi/40); yy=R*sin((0:80)*pi/40);
    for k=1:size(Obj,1)
        plot(Obj(k,1)+xx,Obj(k,2)+yy,'w');
    end
    drawnow; pause(1);

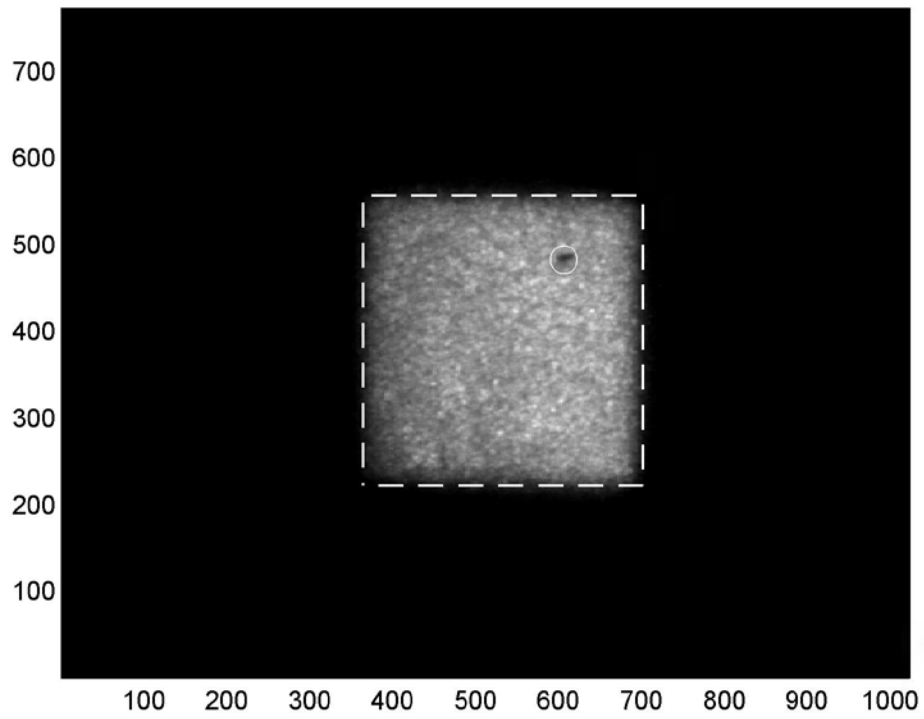
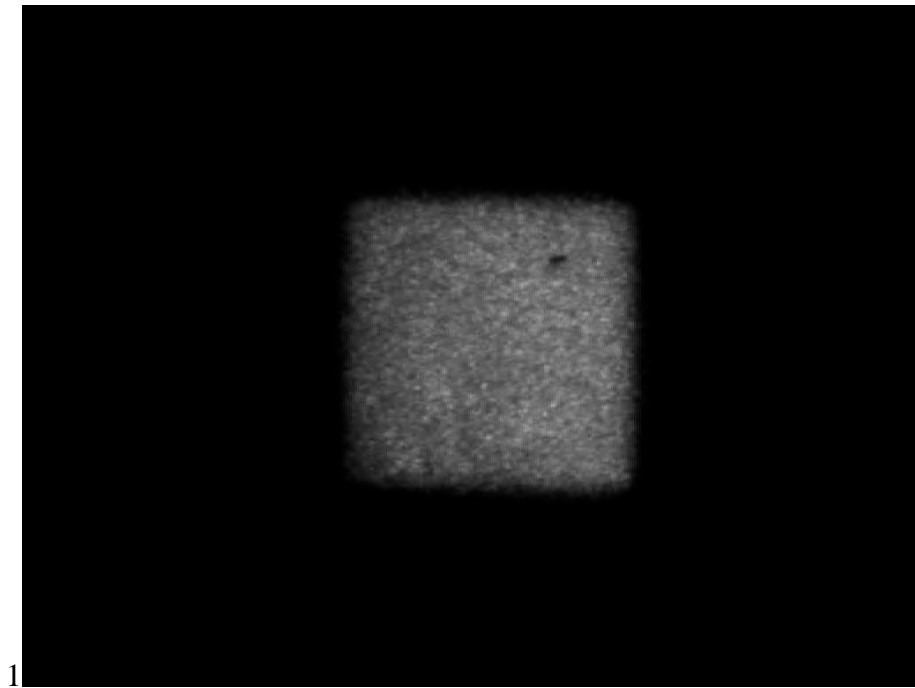
end

```

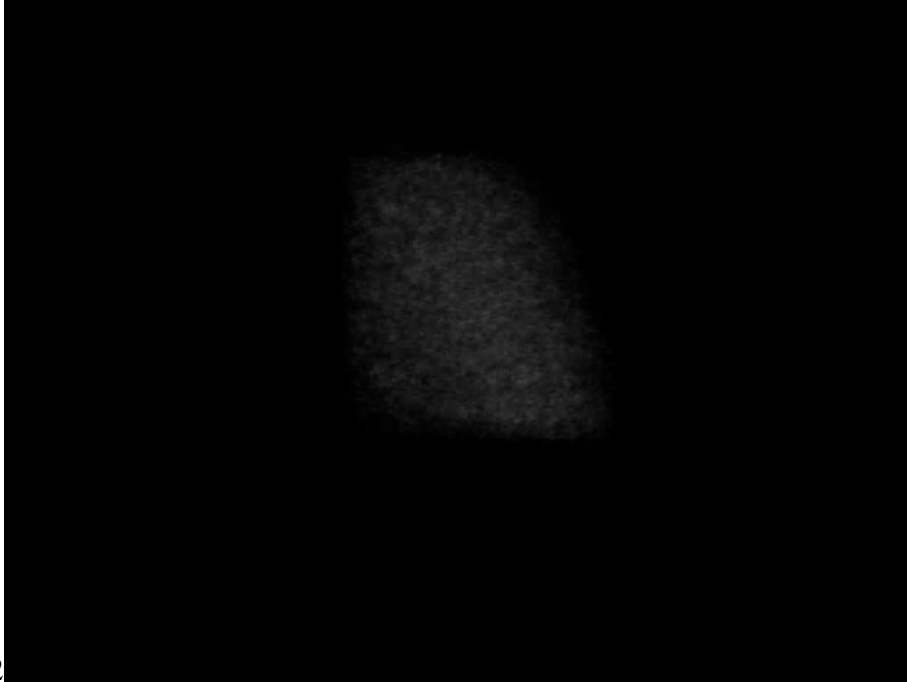
THIS PAGE INTENTIONALLY LEFT BLANK

# APPENDIX C RESULTS FROM 100 IMAGES

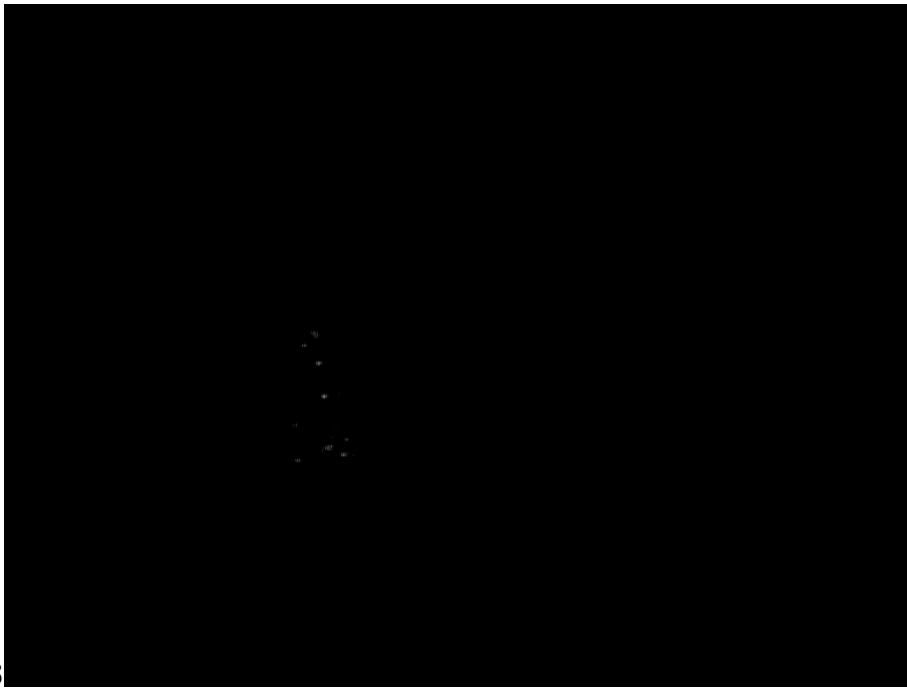
## A. IMAGES



1



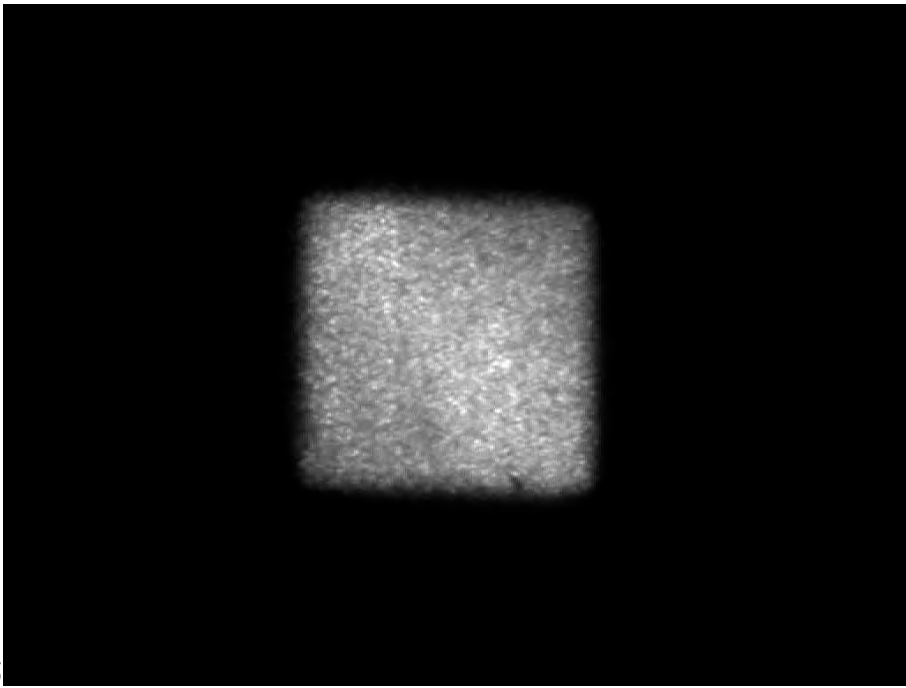
2



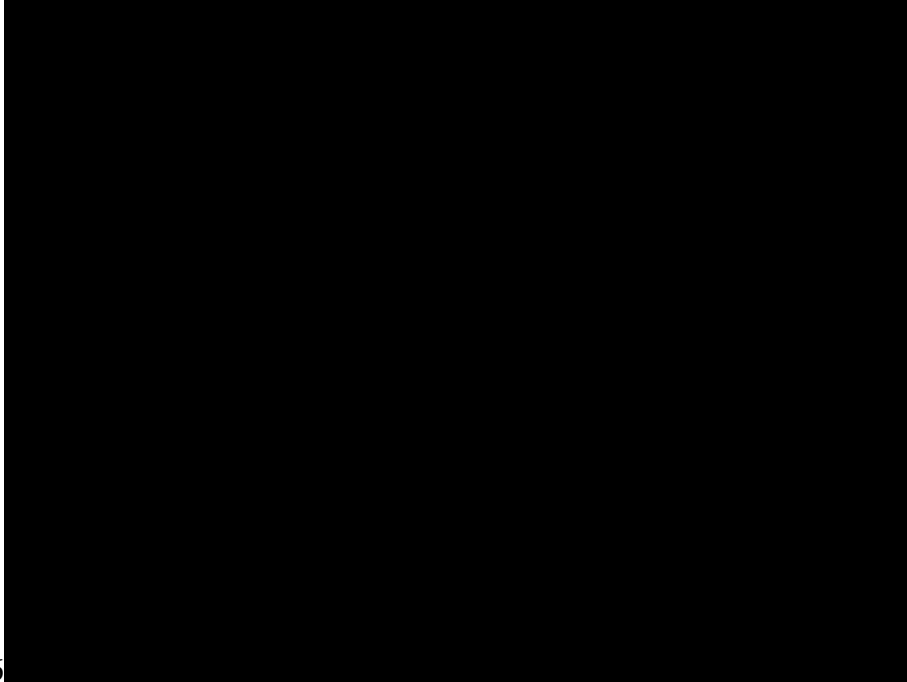
3



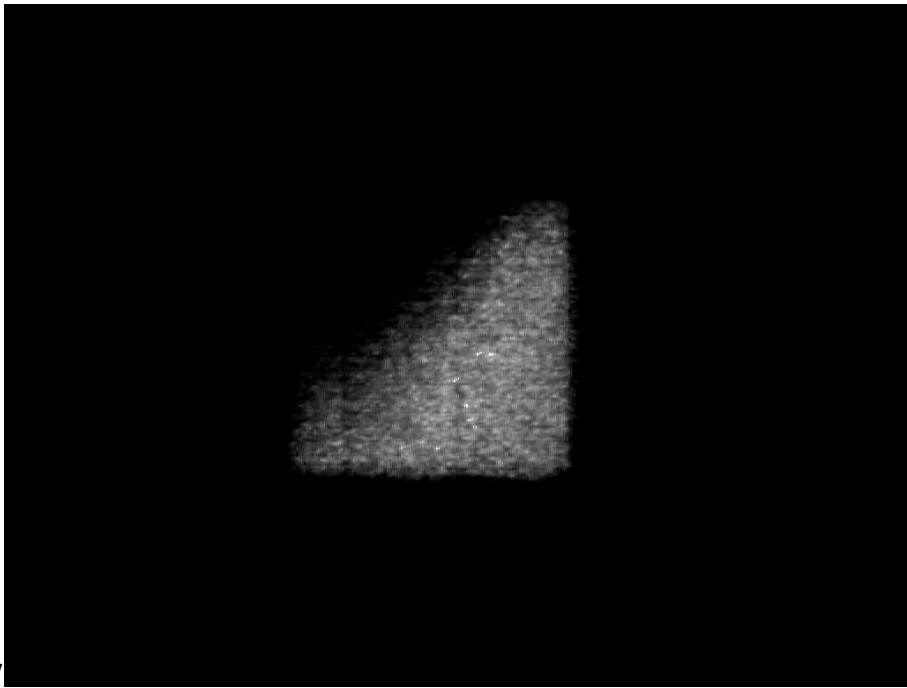
4



5

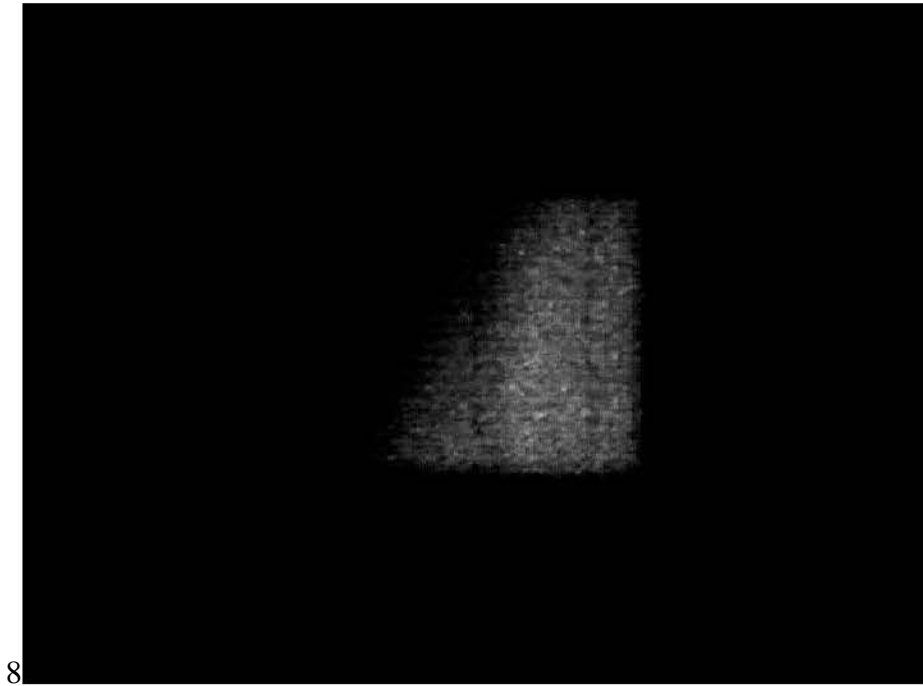
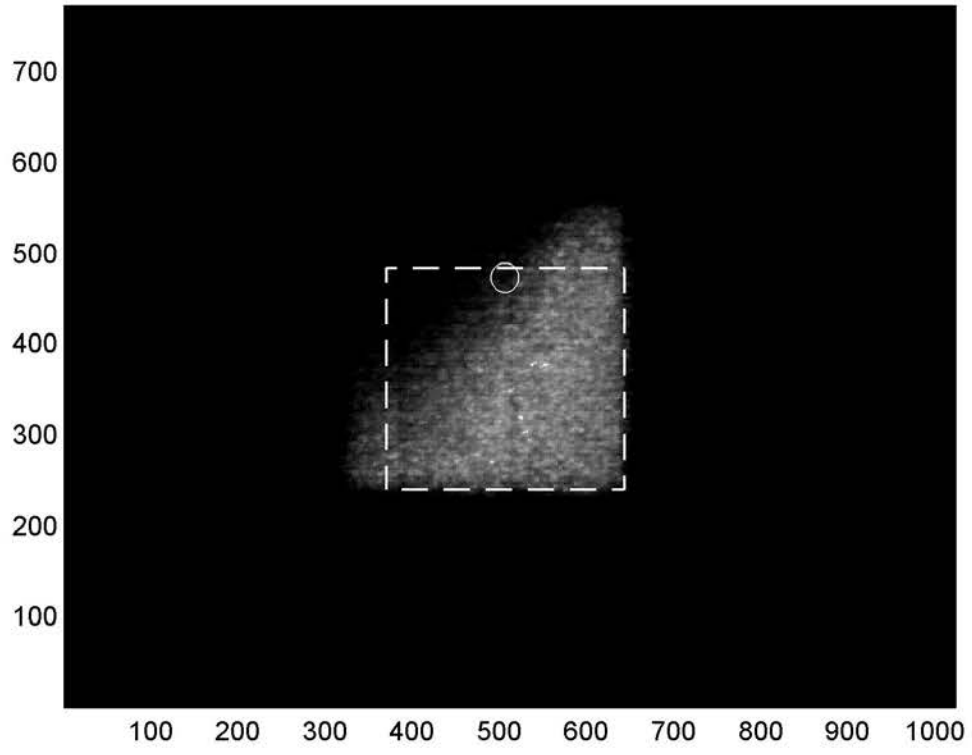


6



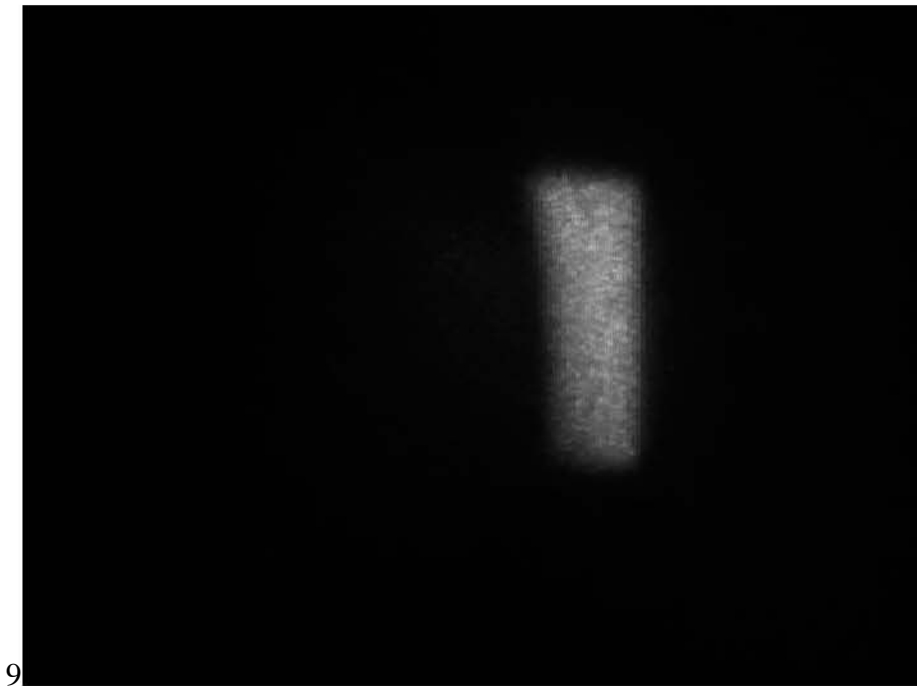
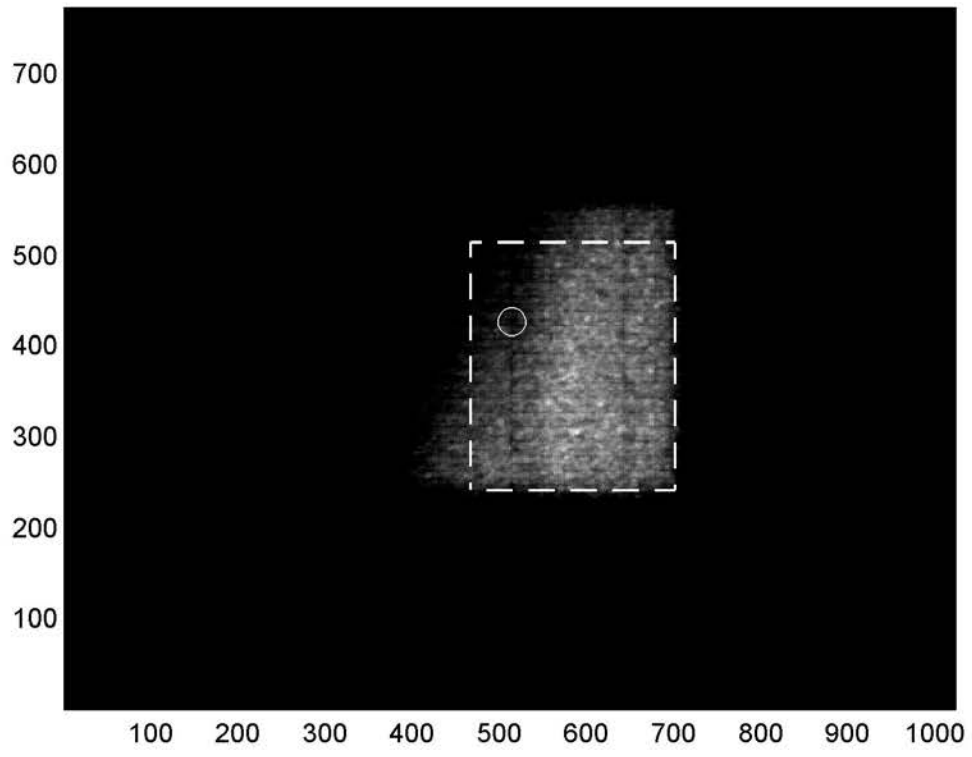
7

7



77

8

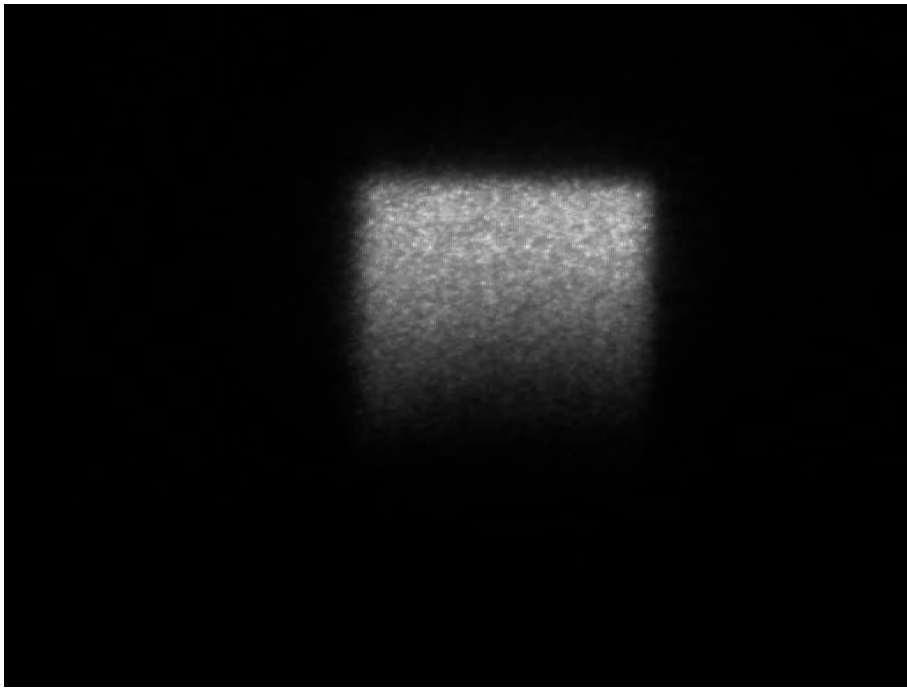


9

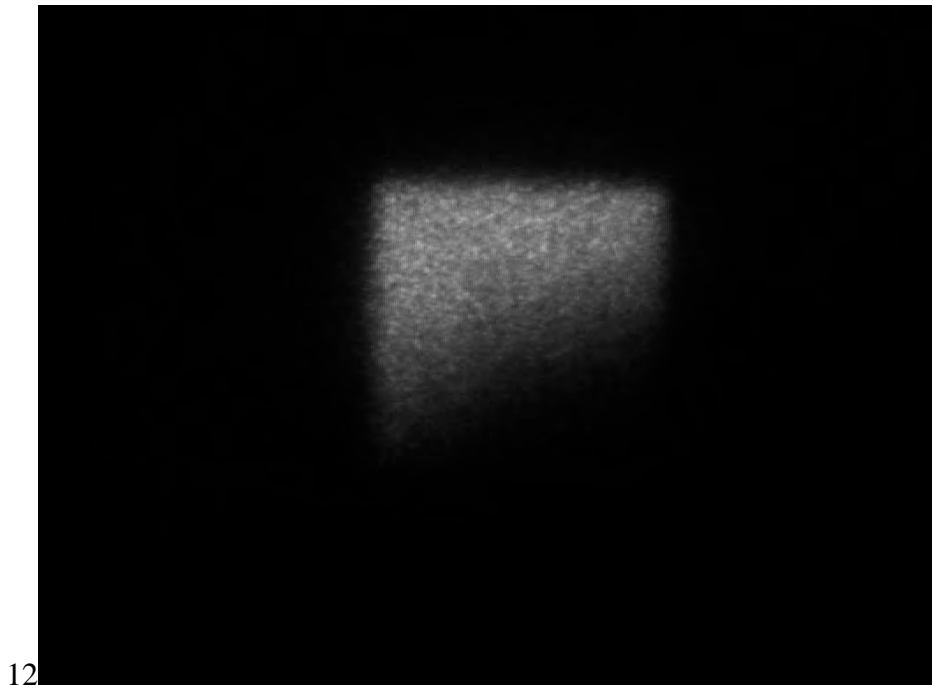
78



10



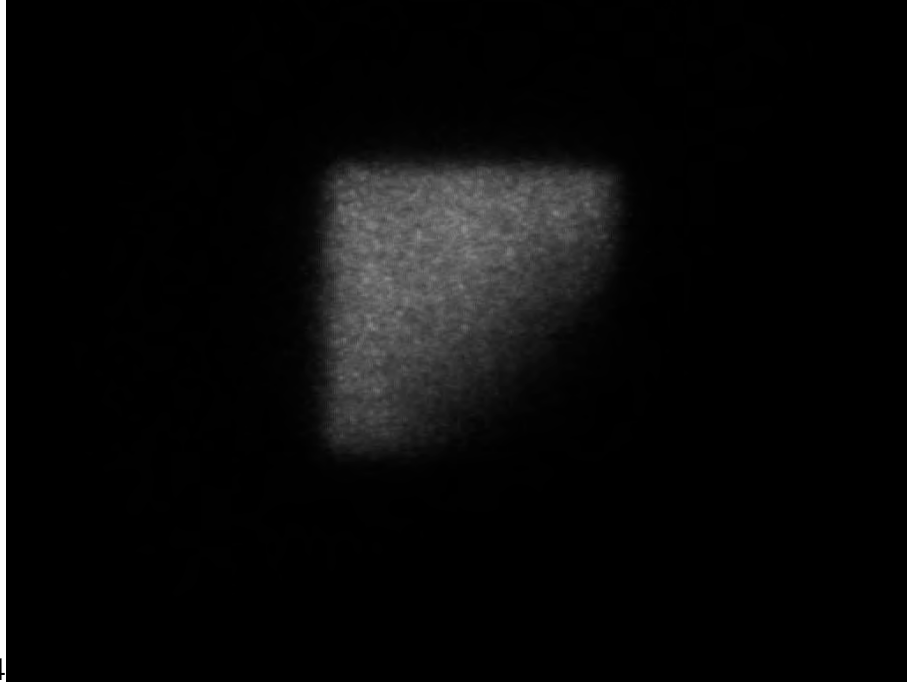
11



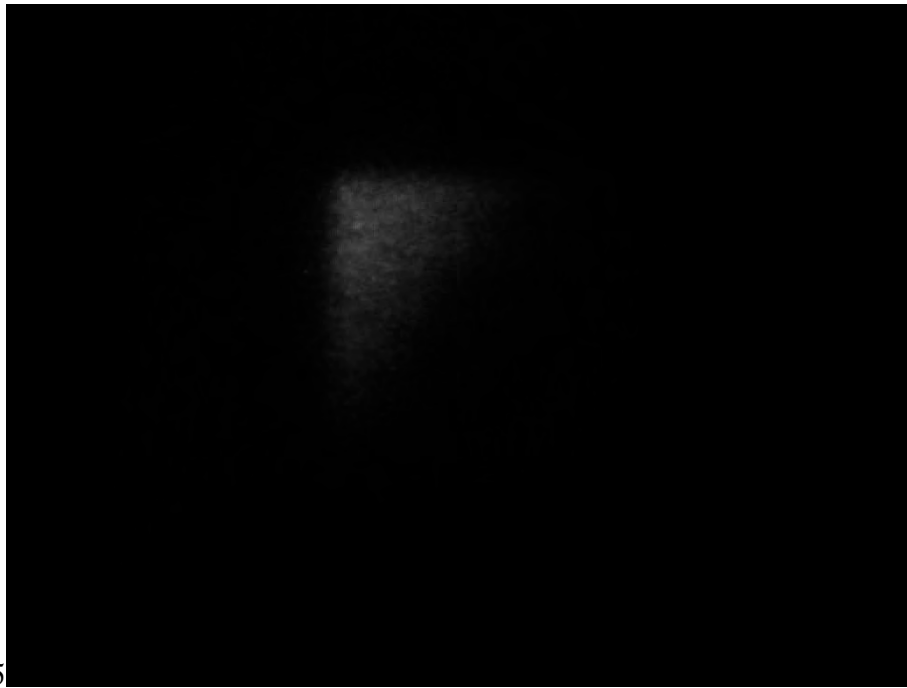
12



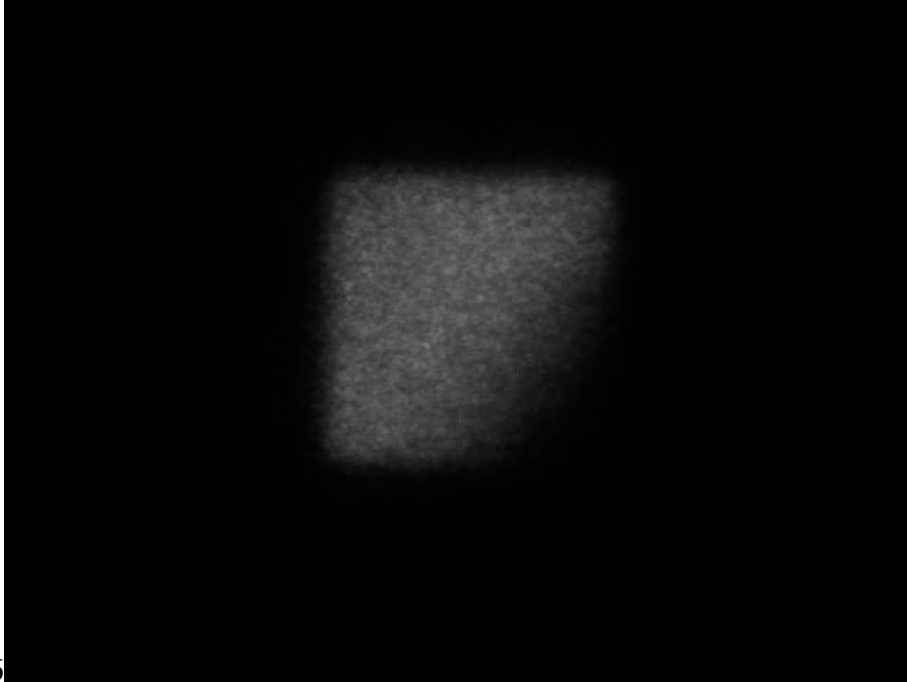
13



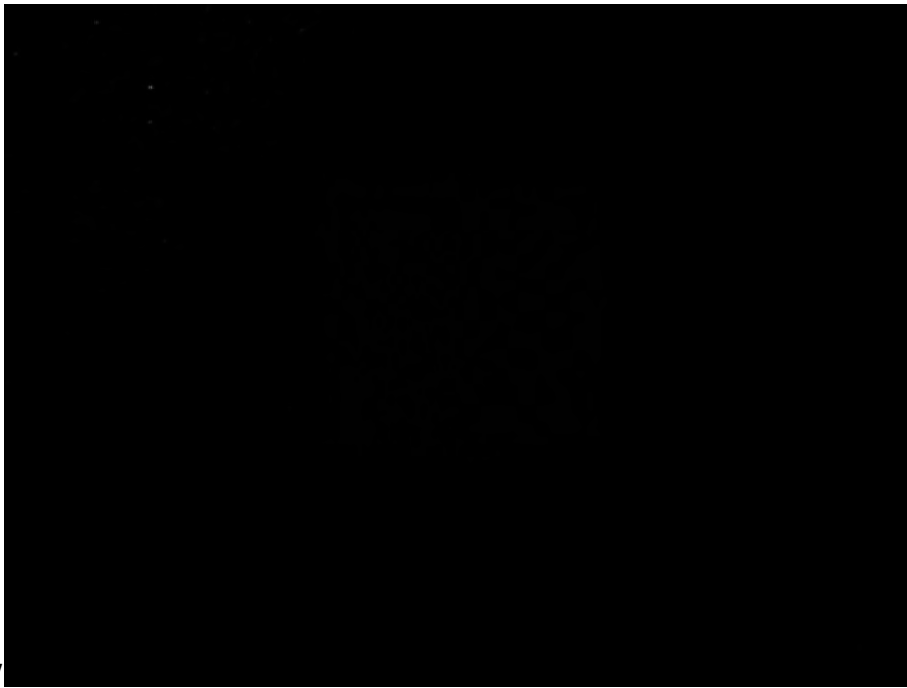
14



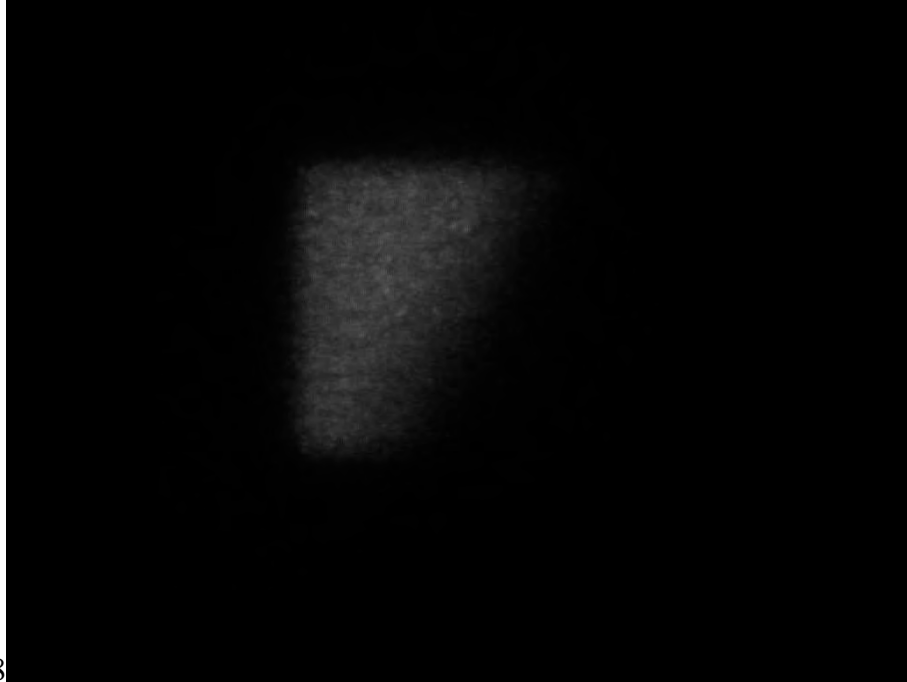
15



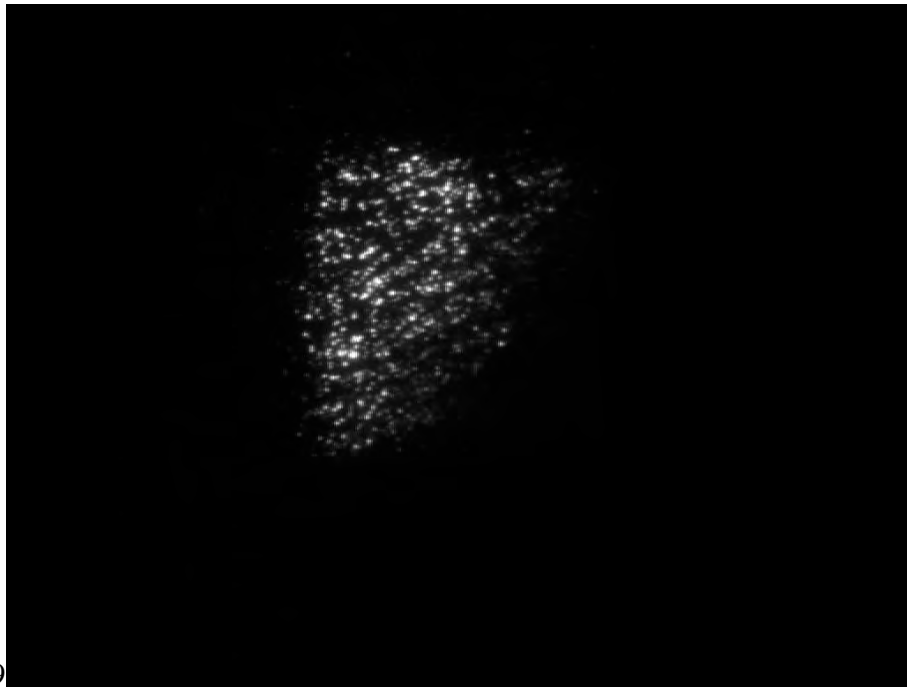
16



17

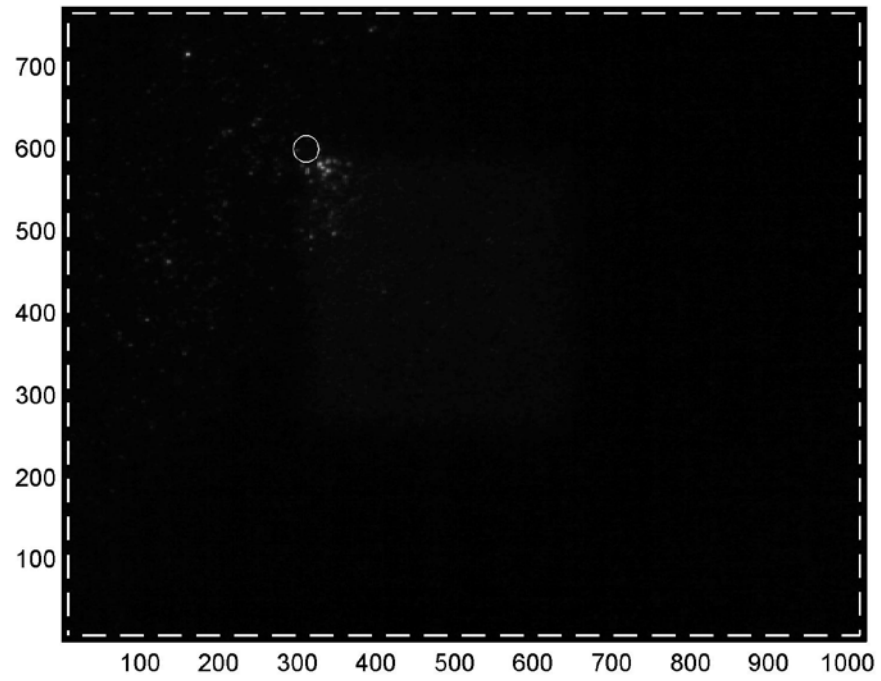


18

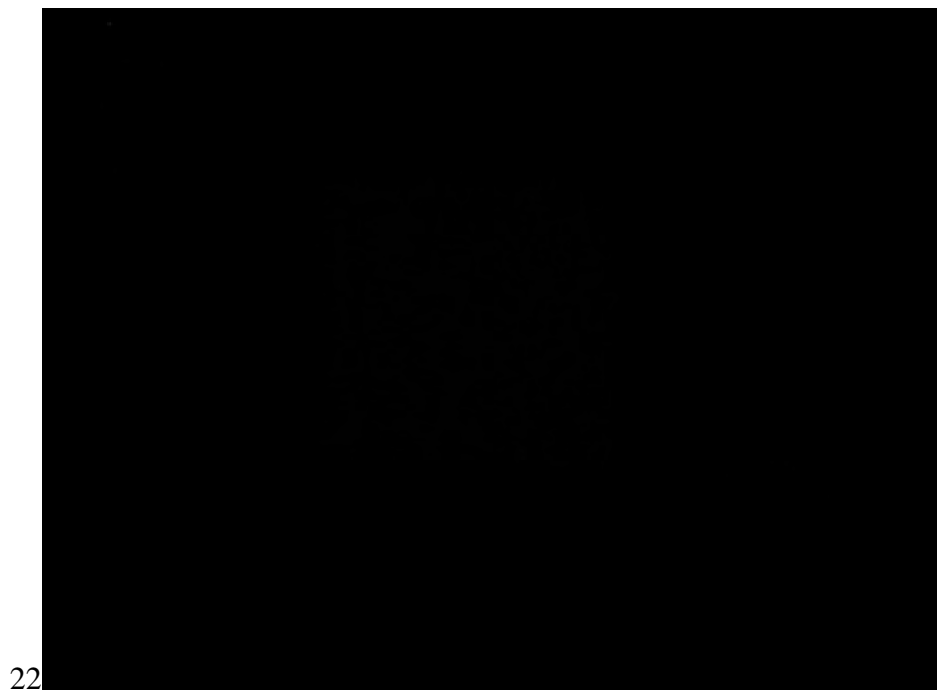


19





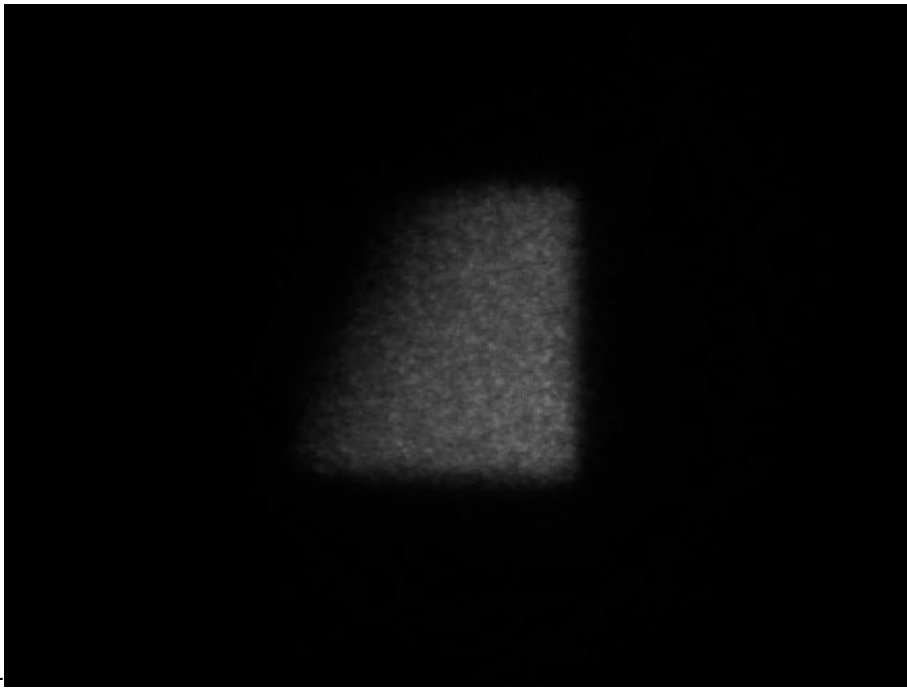
21



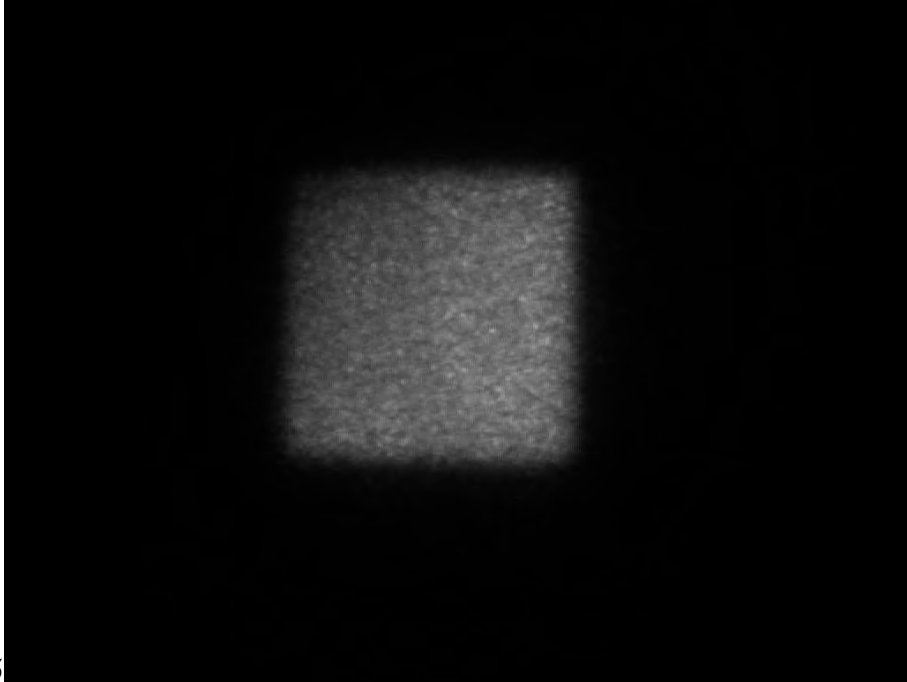
22



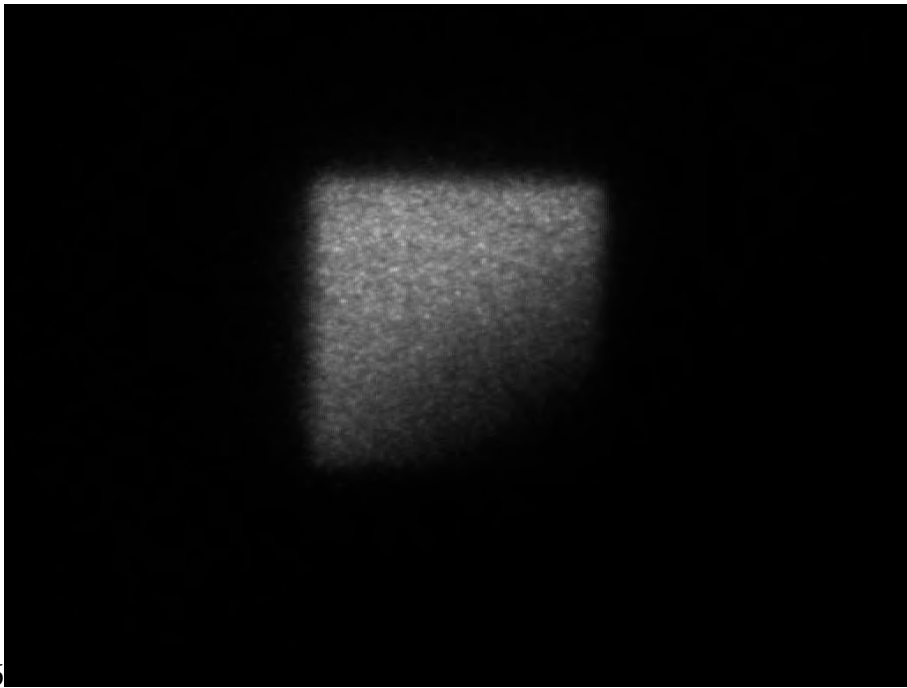
23



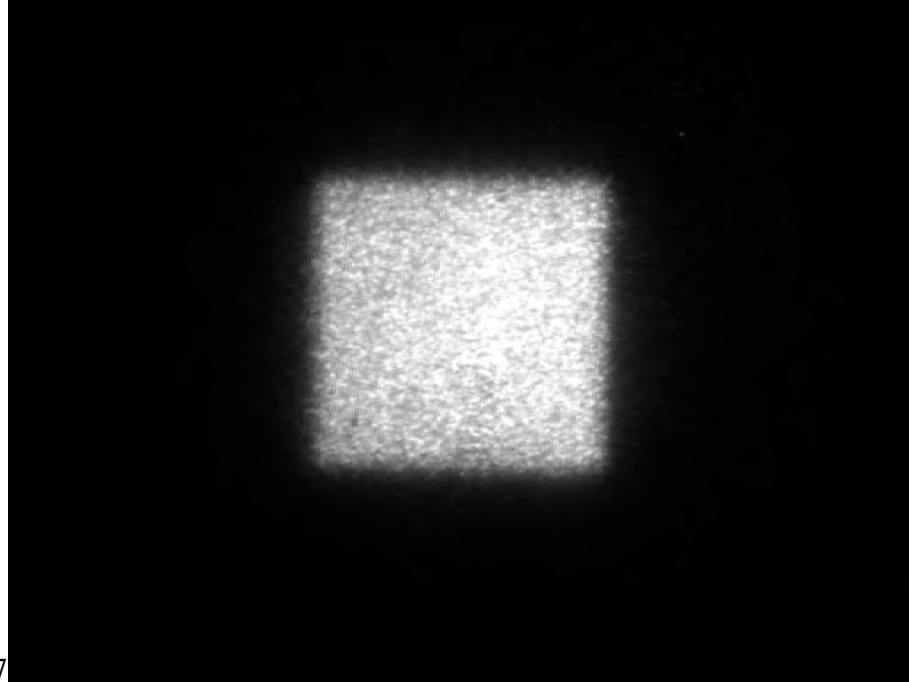
24



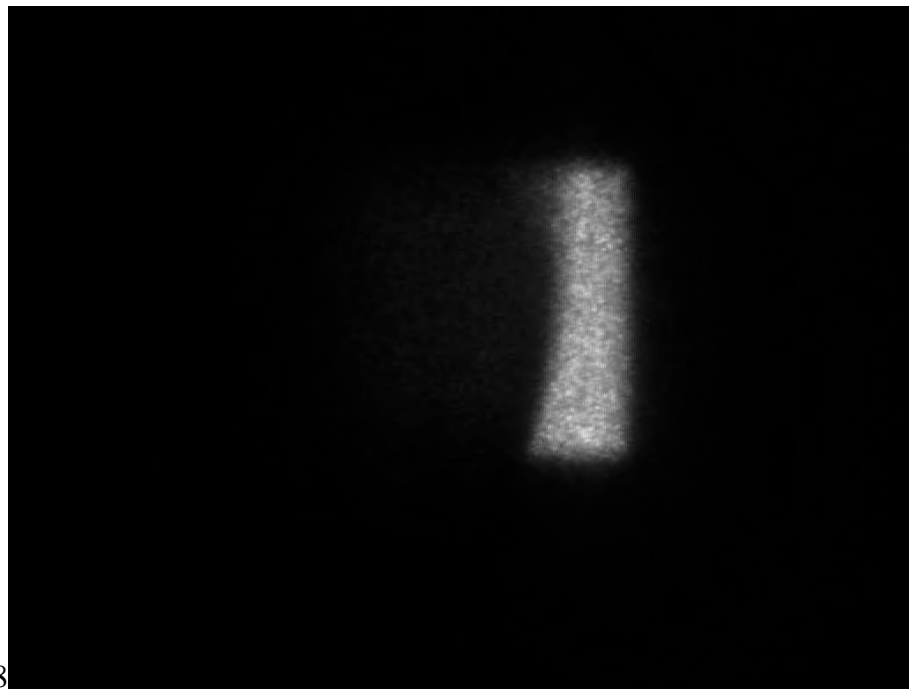
25



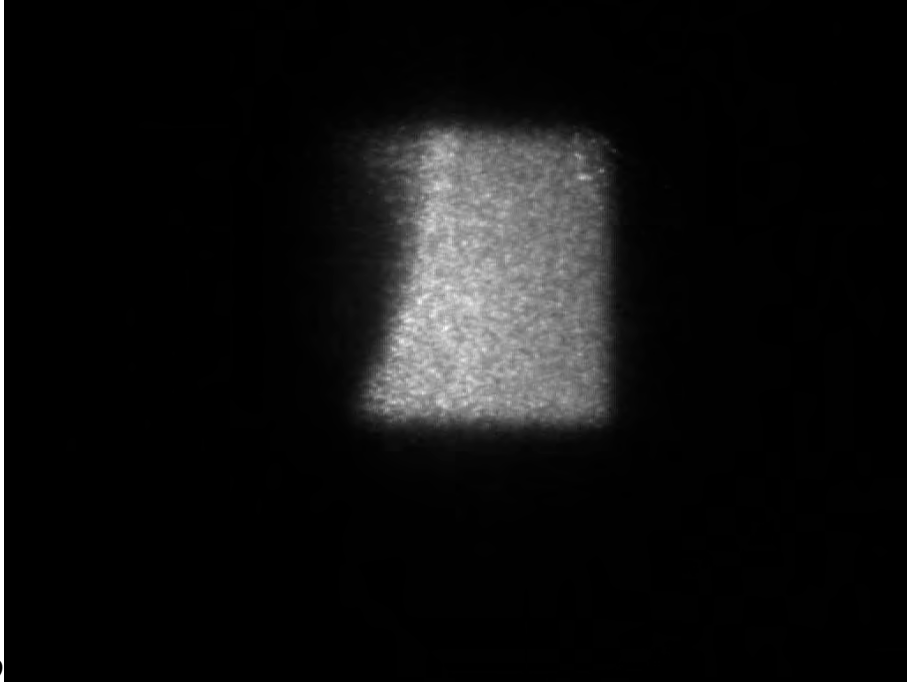
26



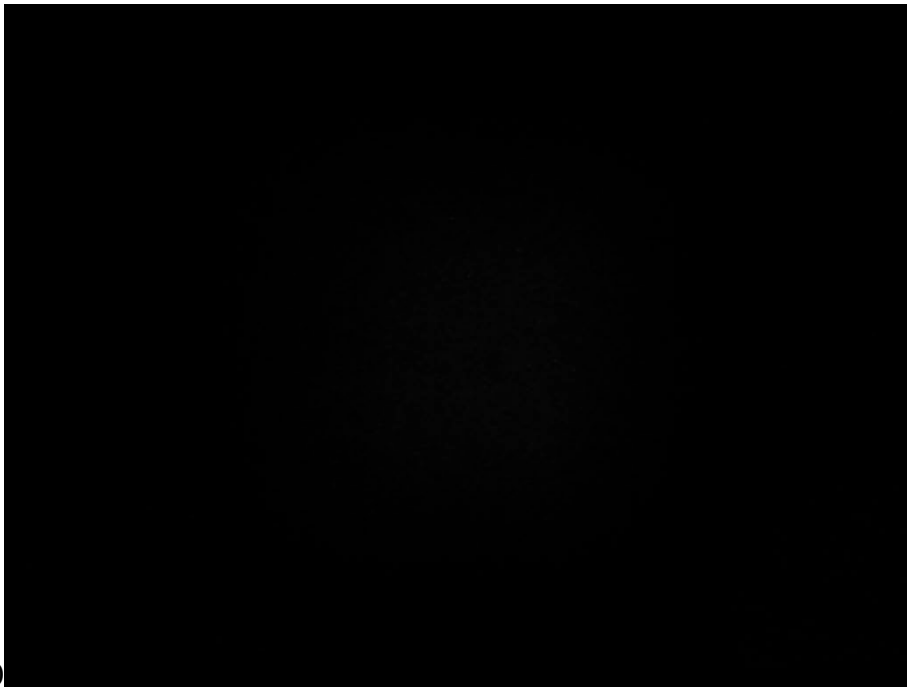
27



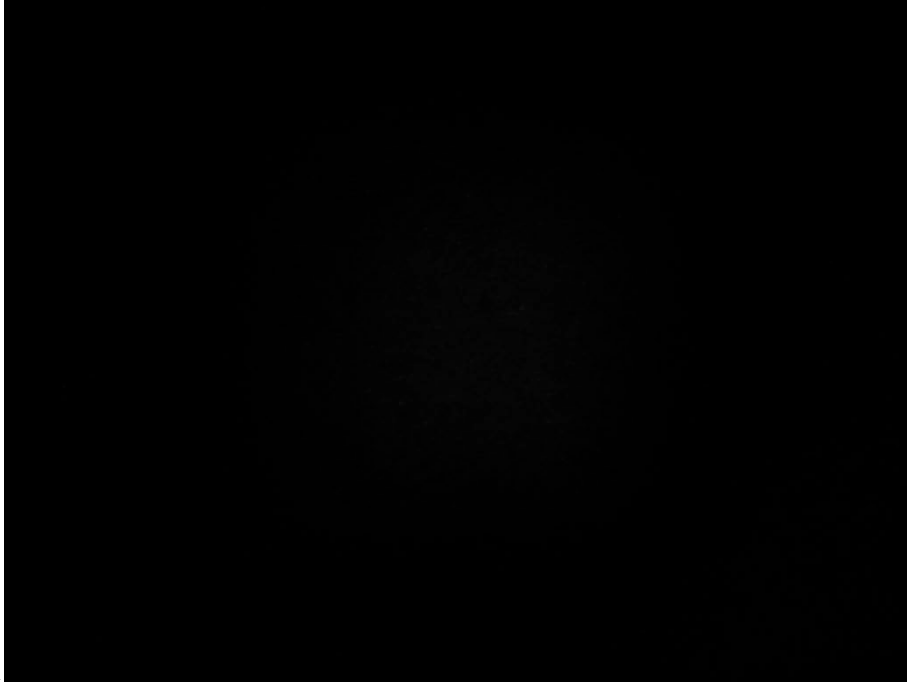
28



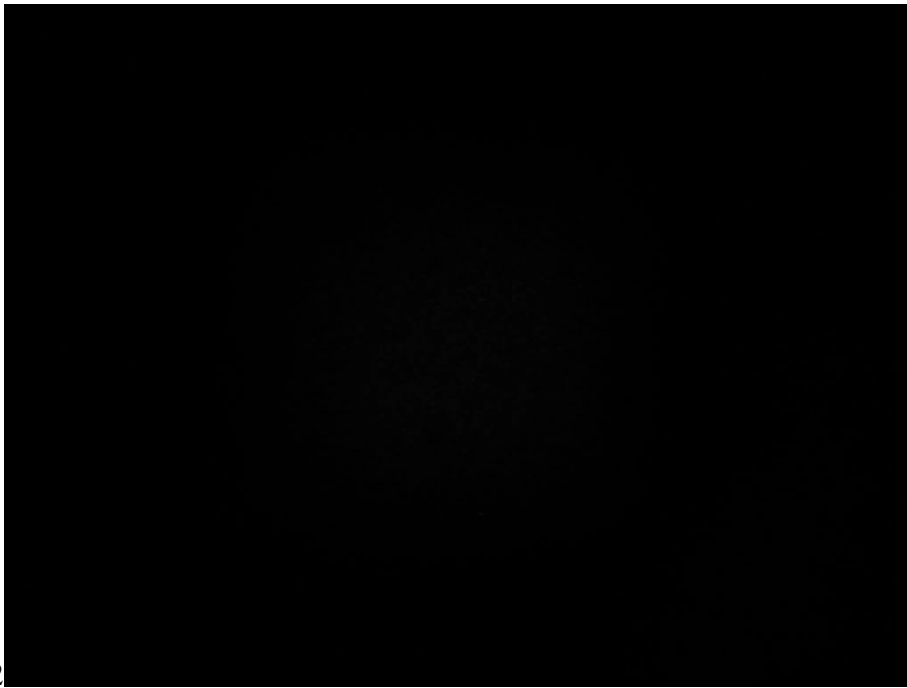
29



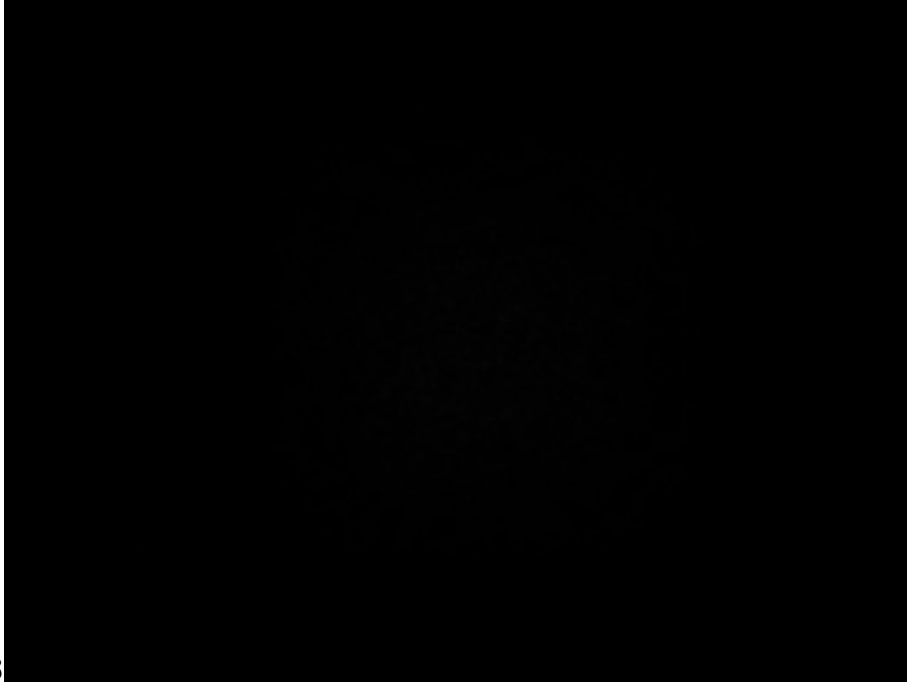
30



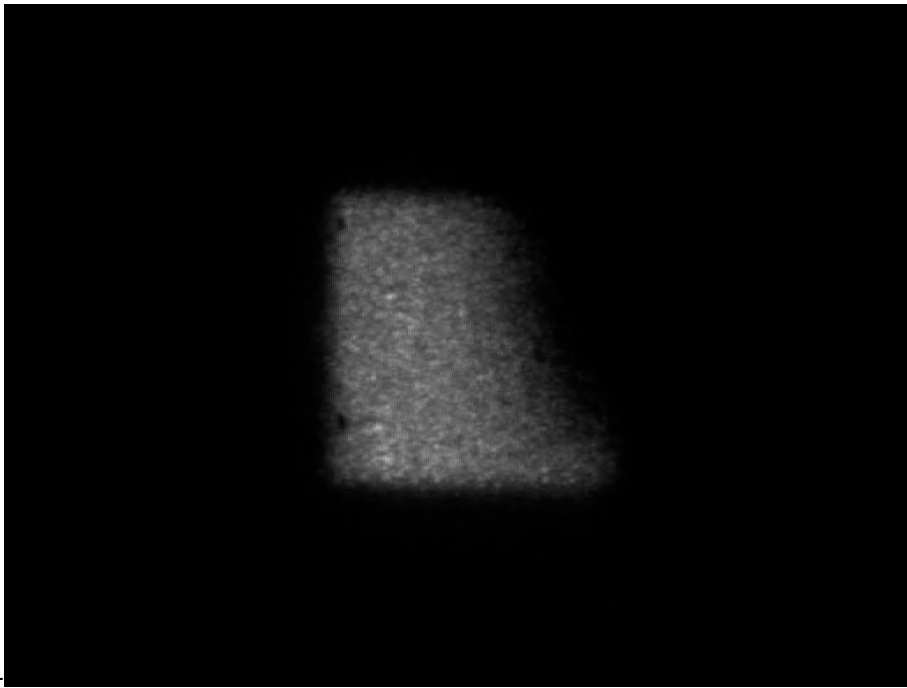
31



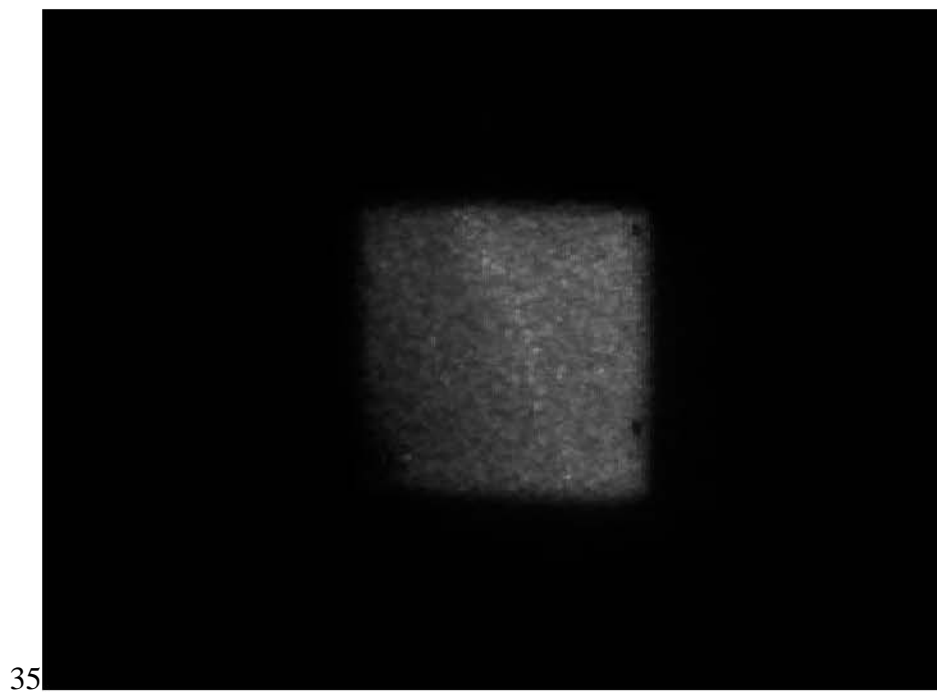
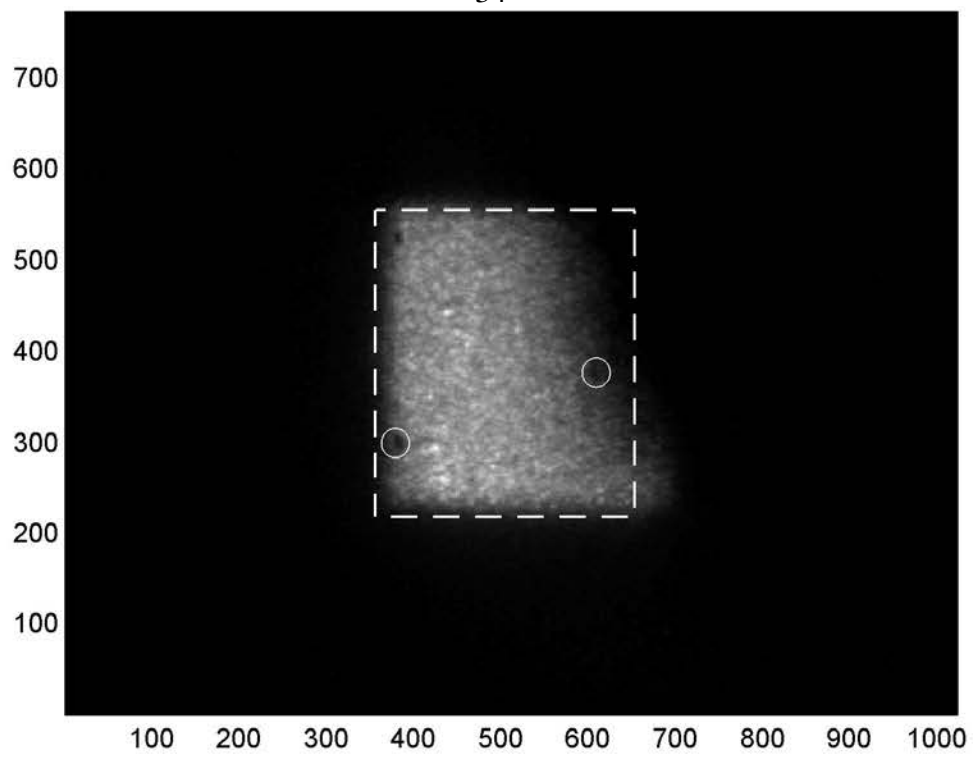
32



33

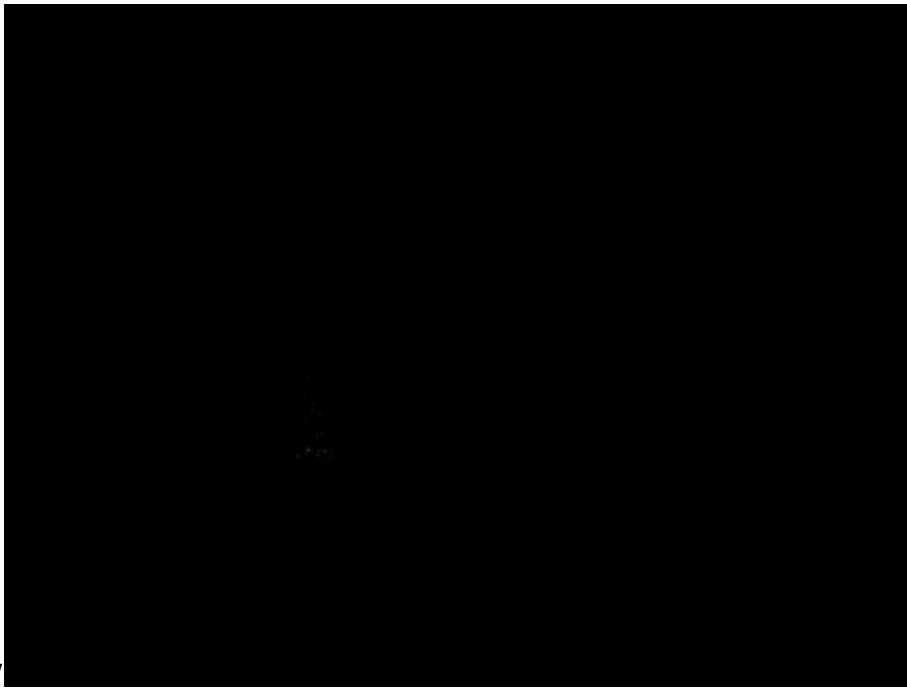


34

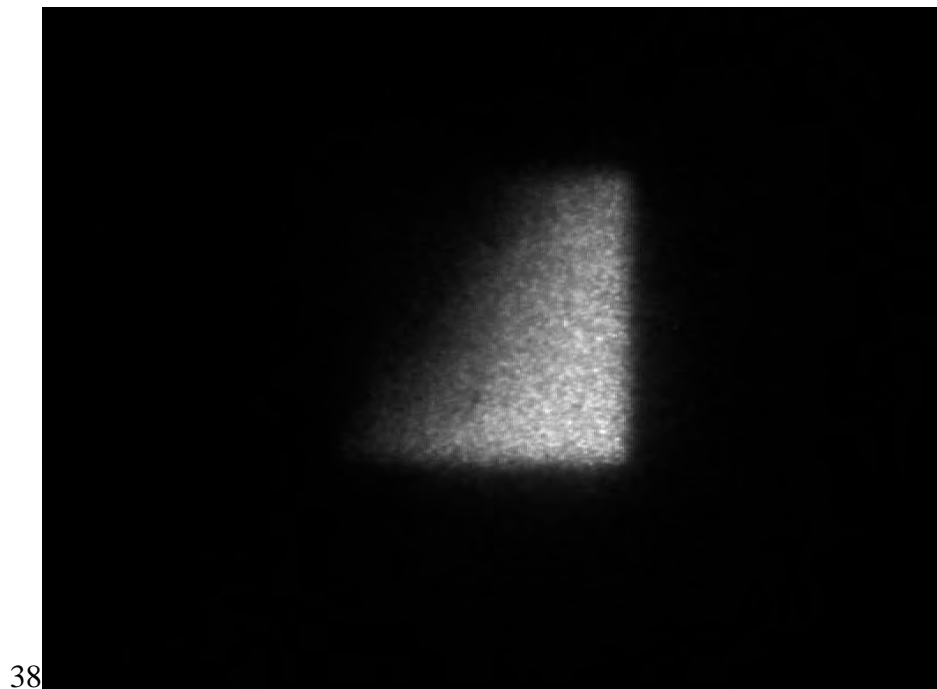




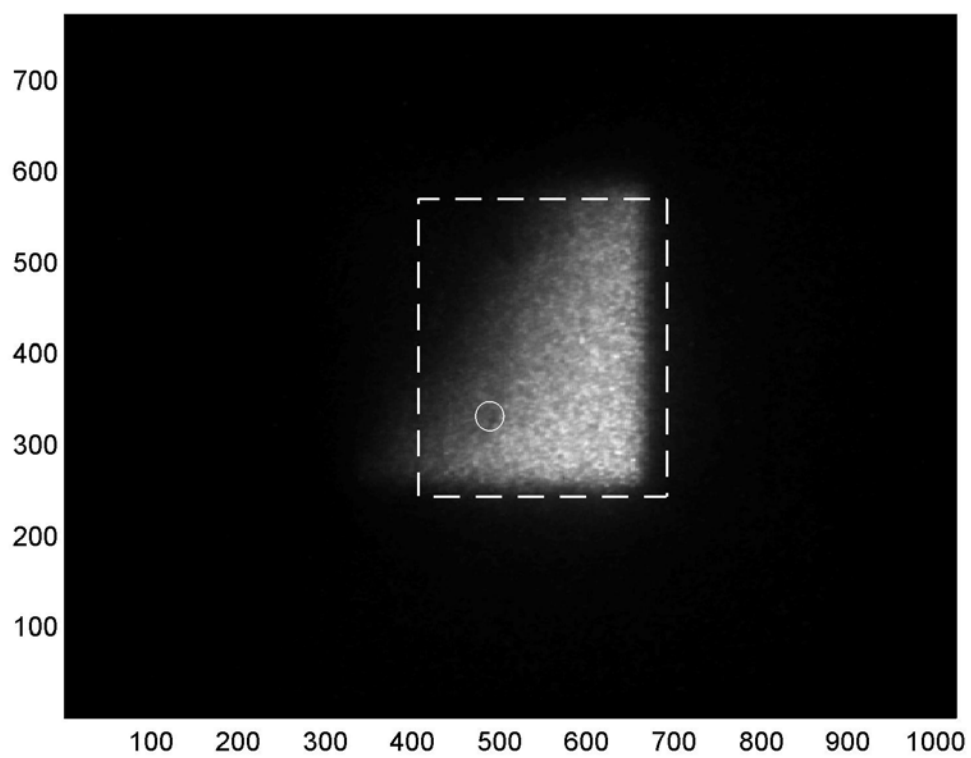
36



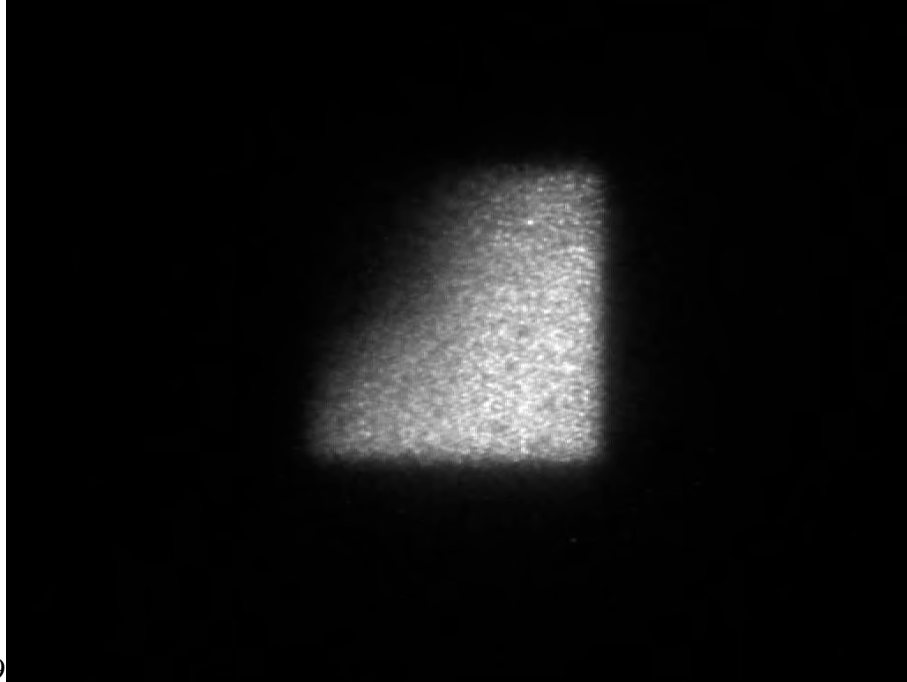
37



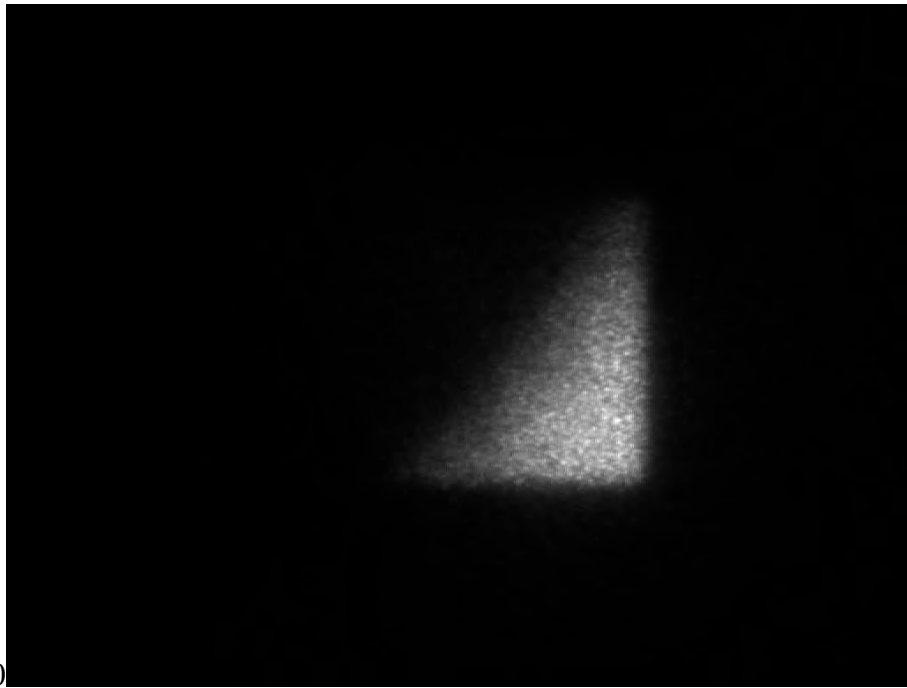
38



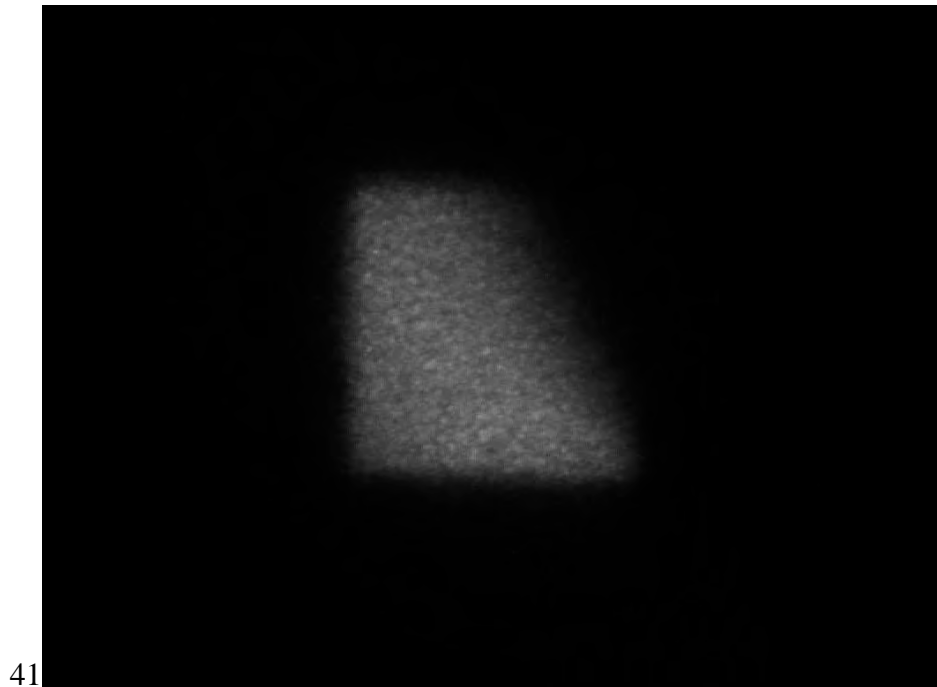
94



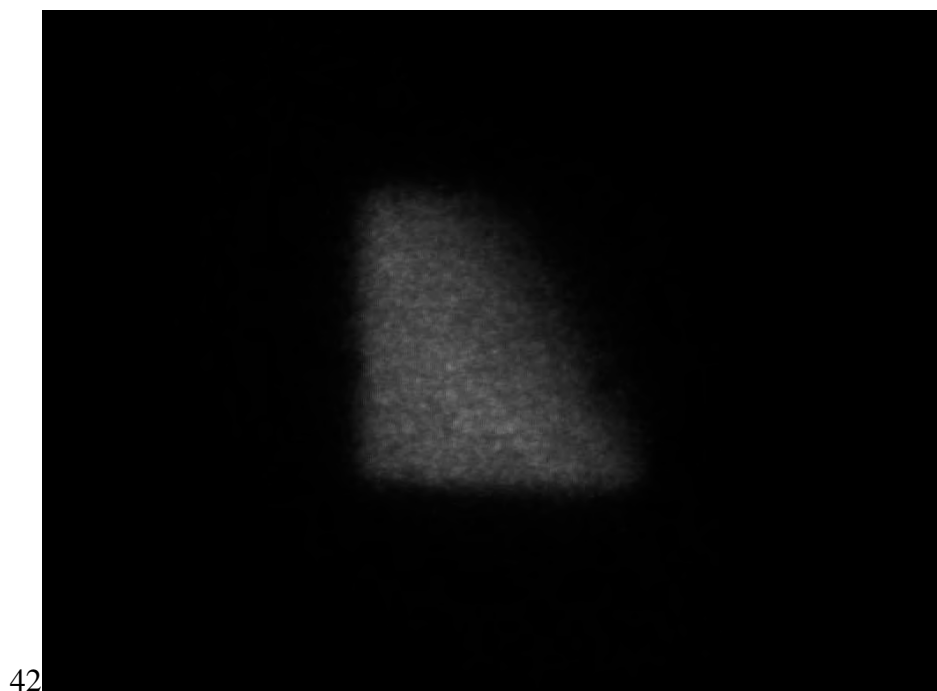
39



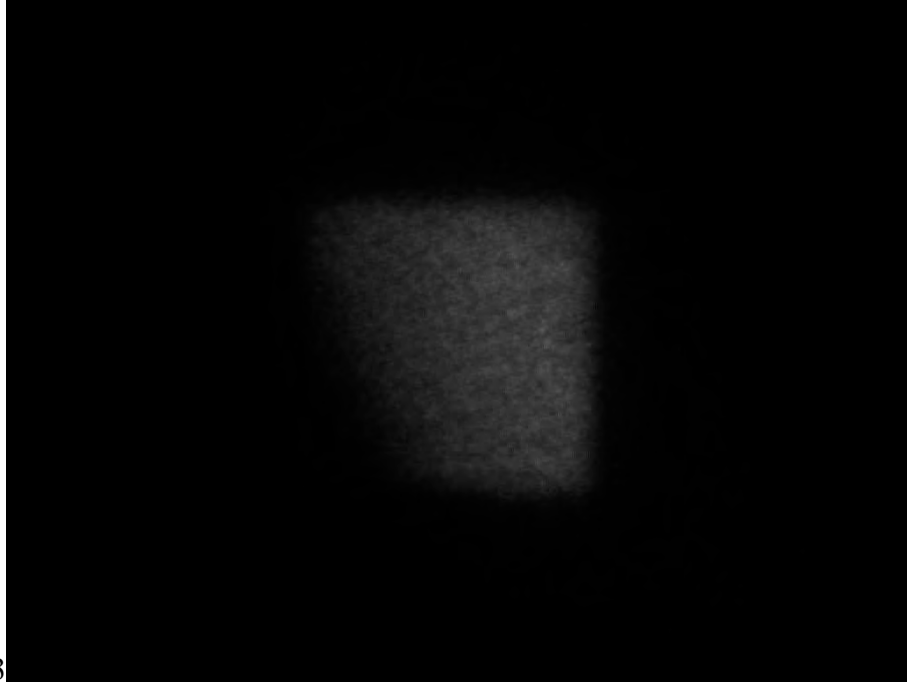
40



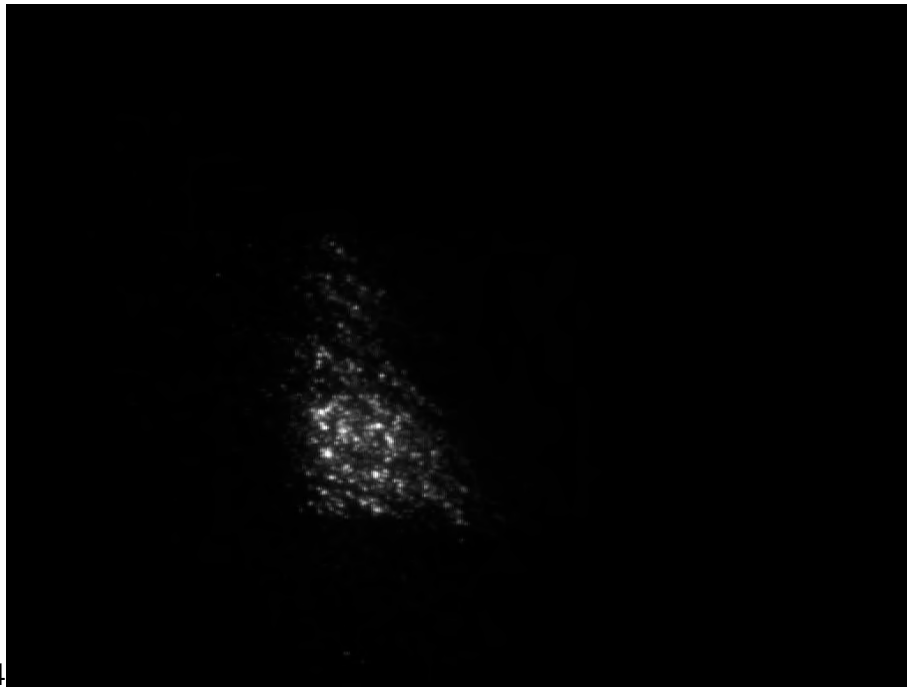
41



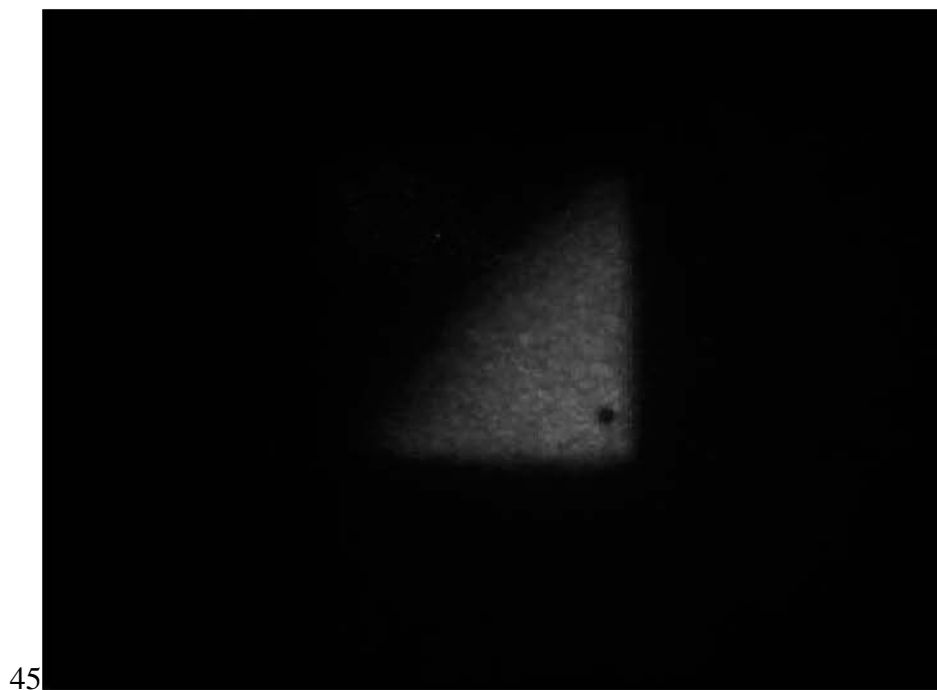
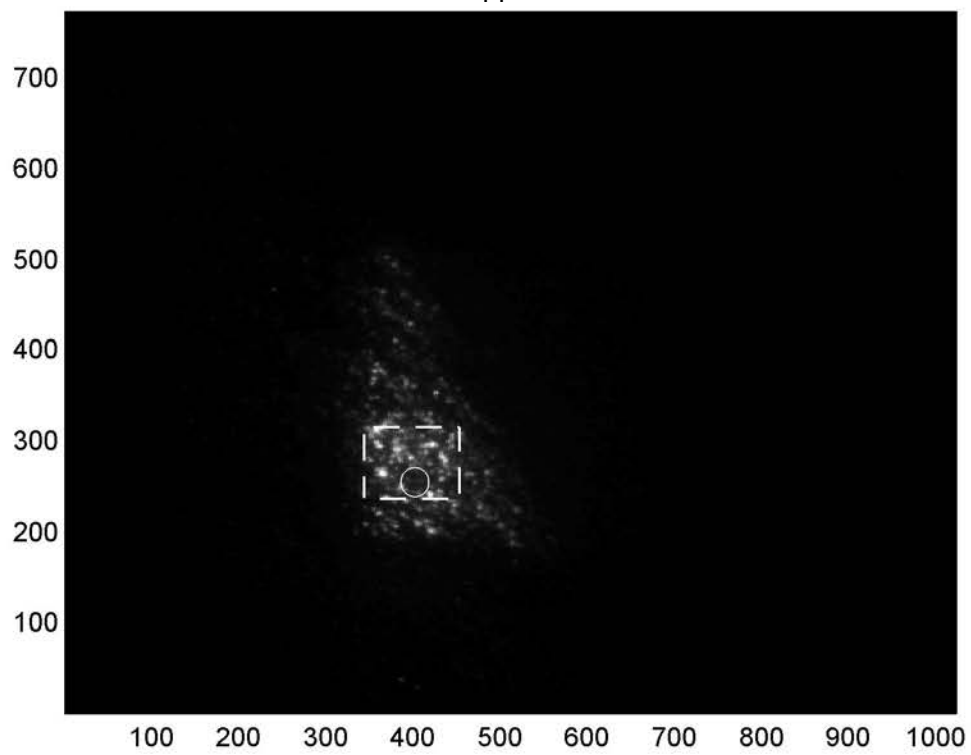
42



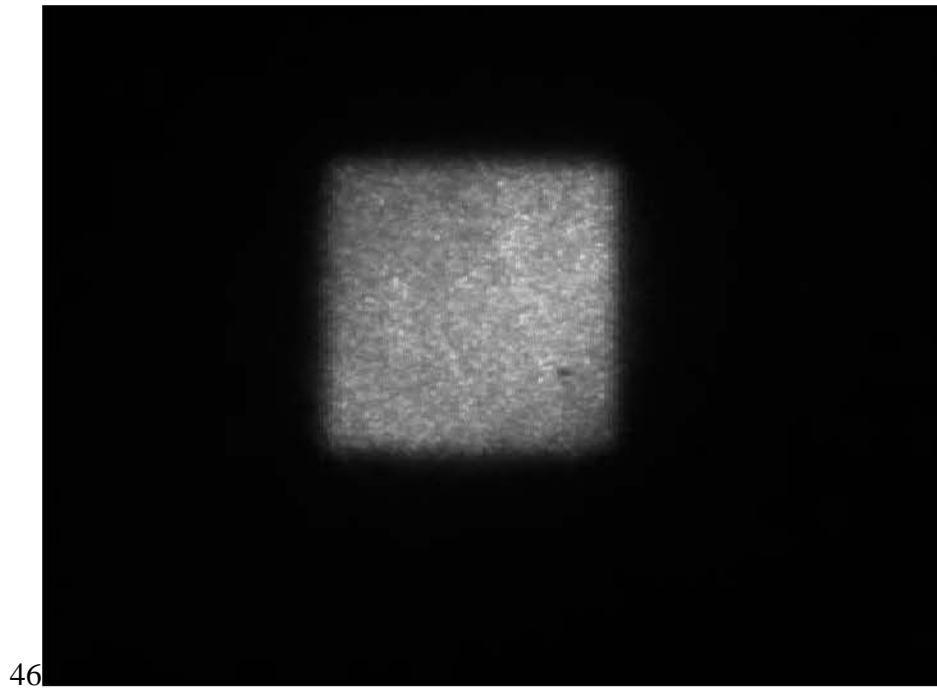
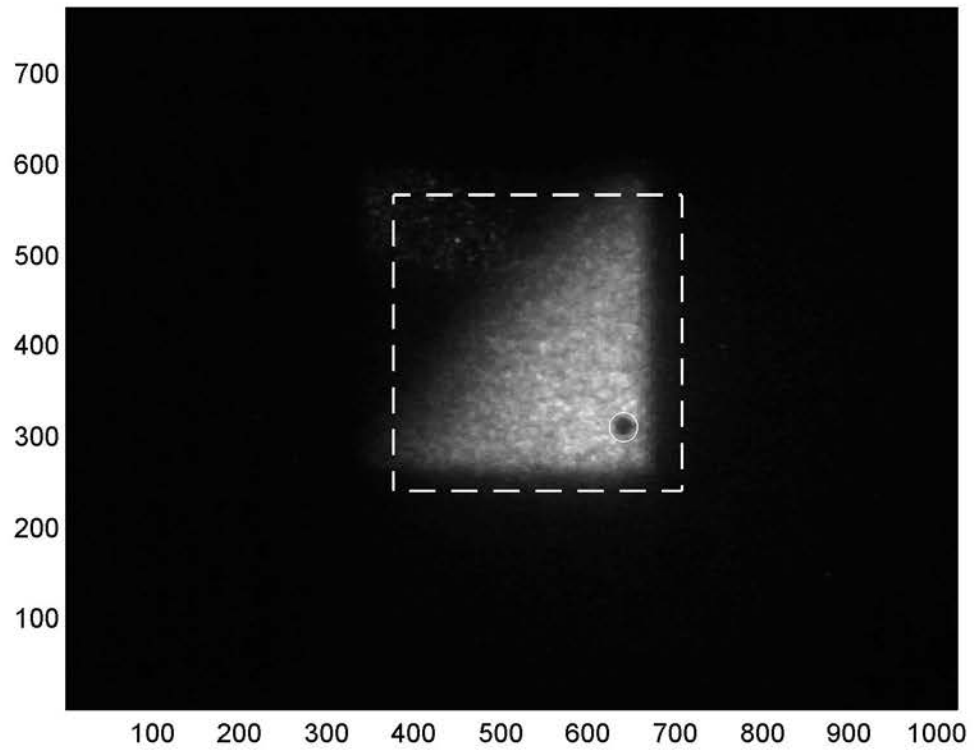
43



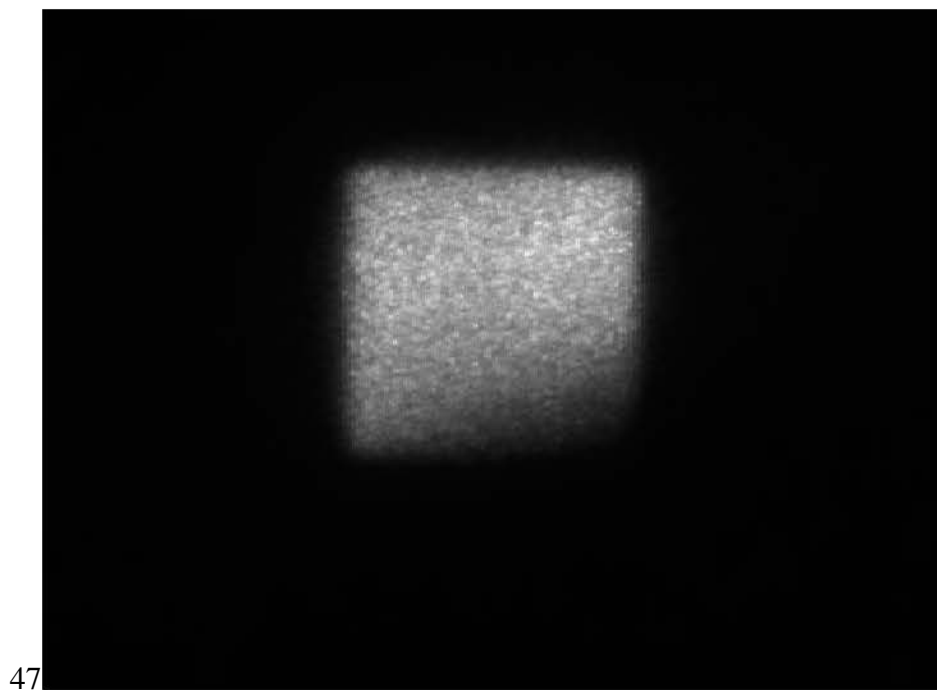
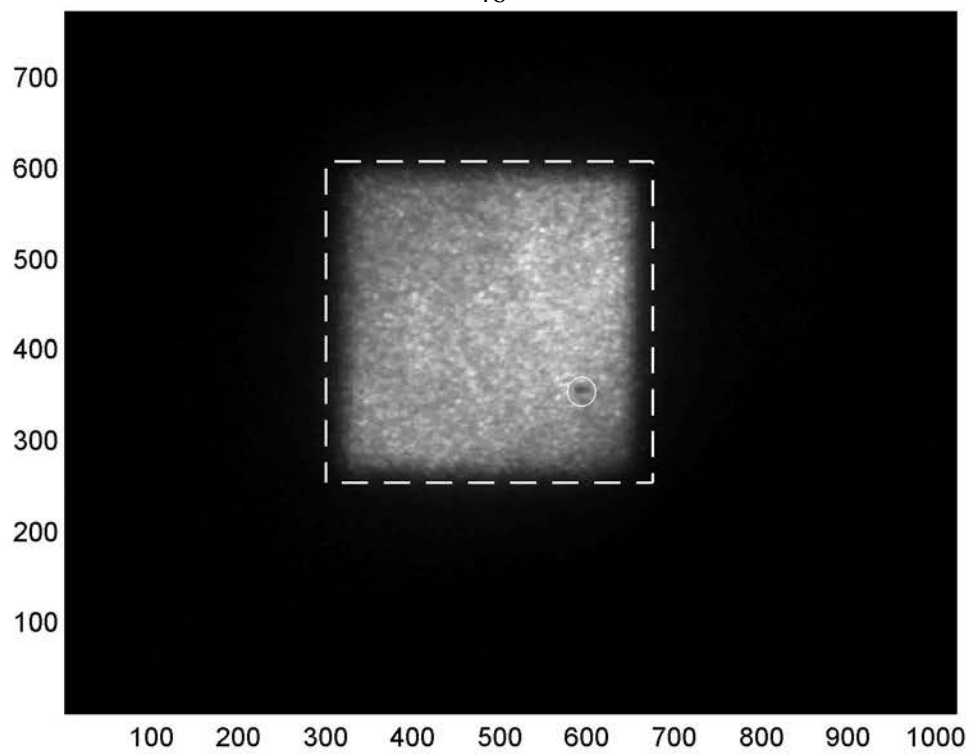
44

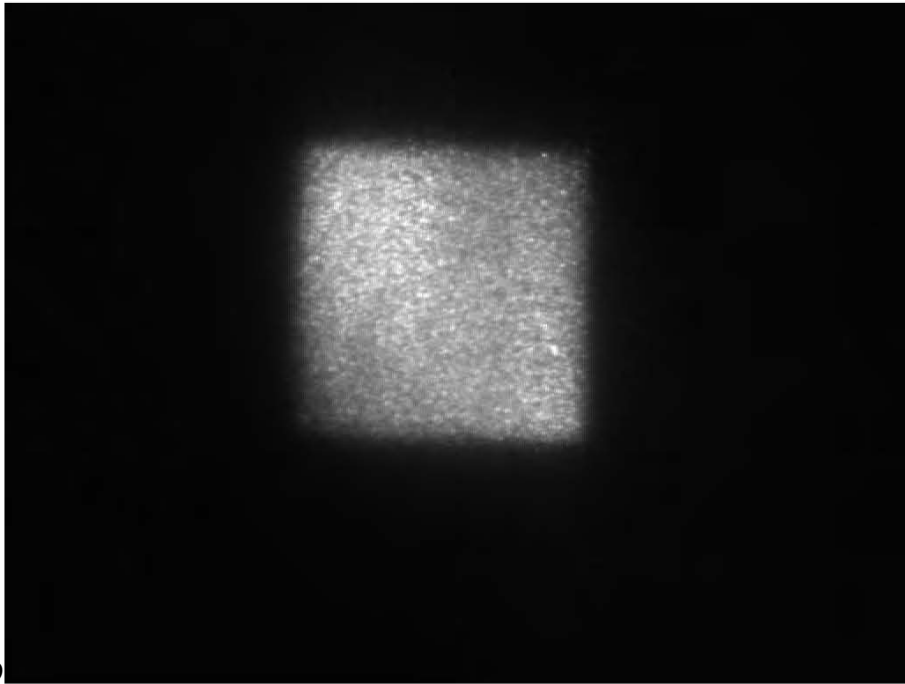
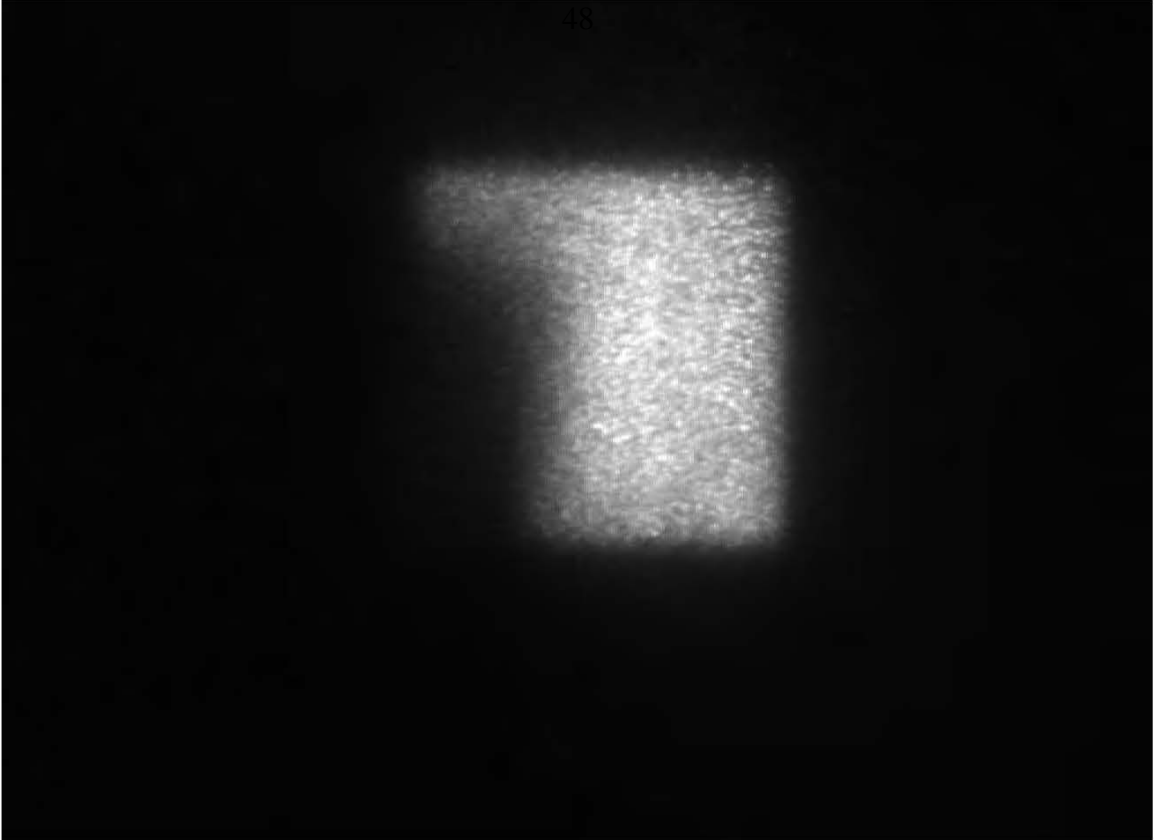


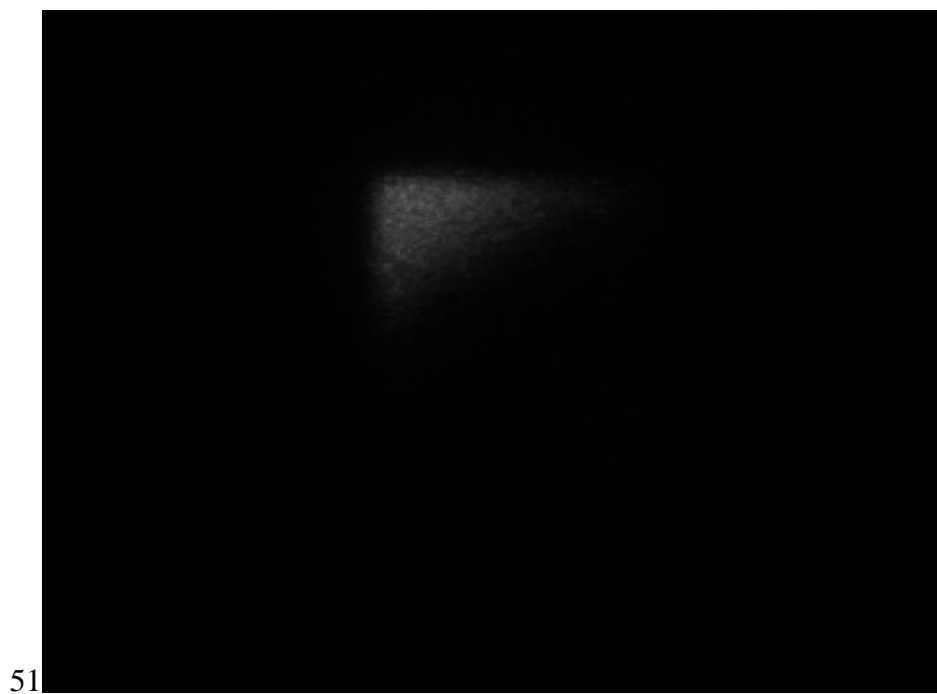
45 omp  
45



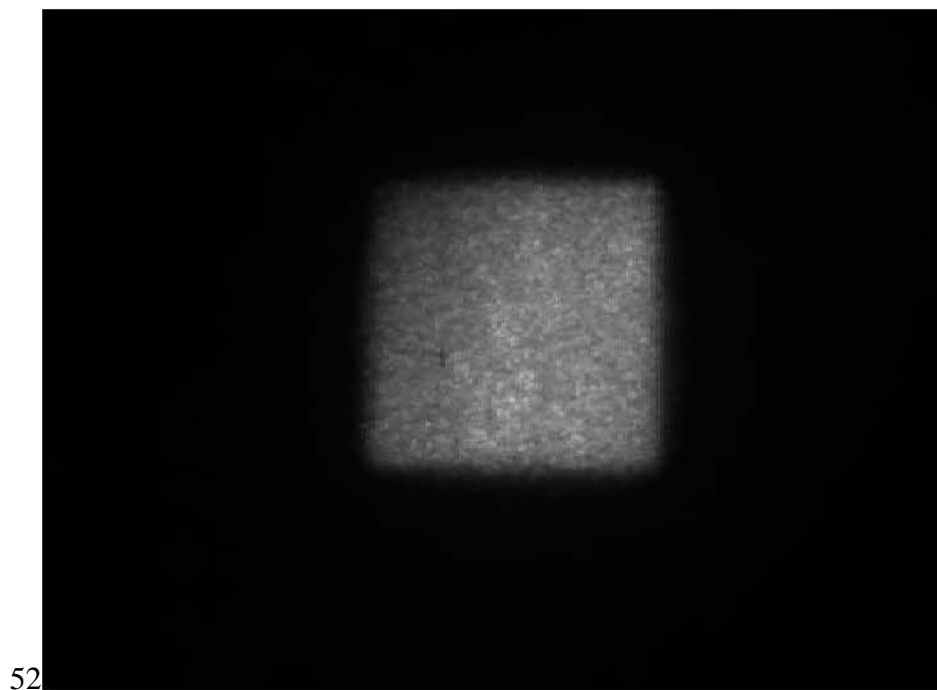
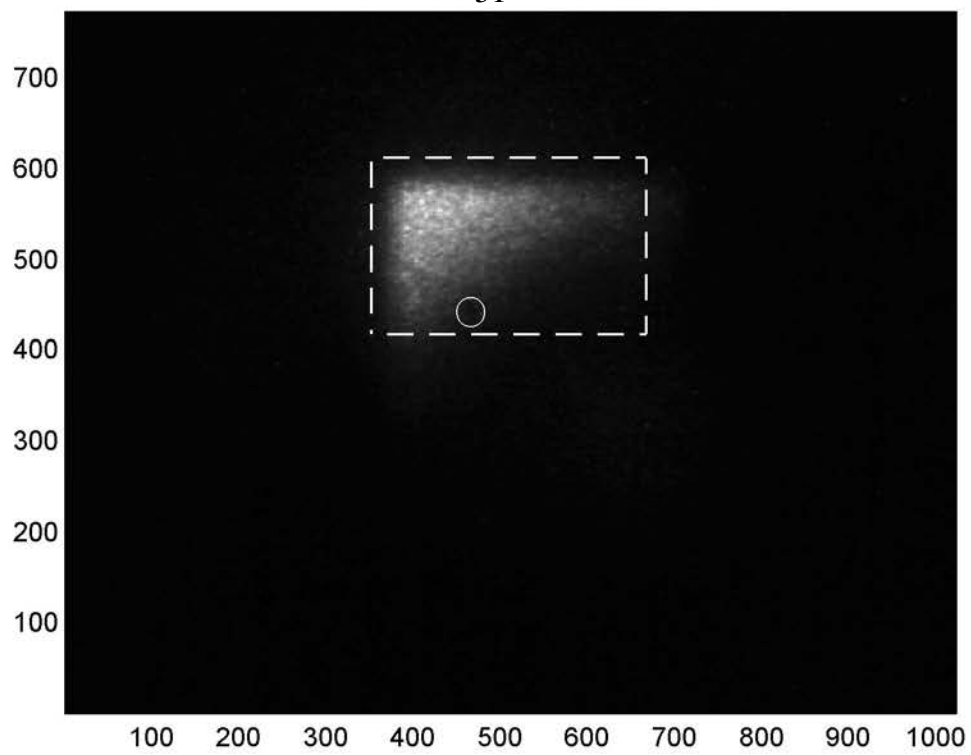
46



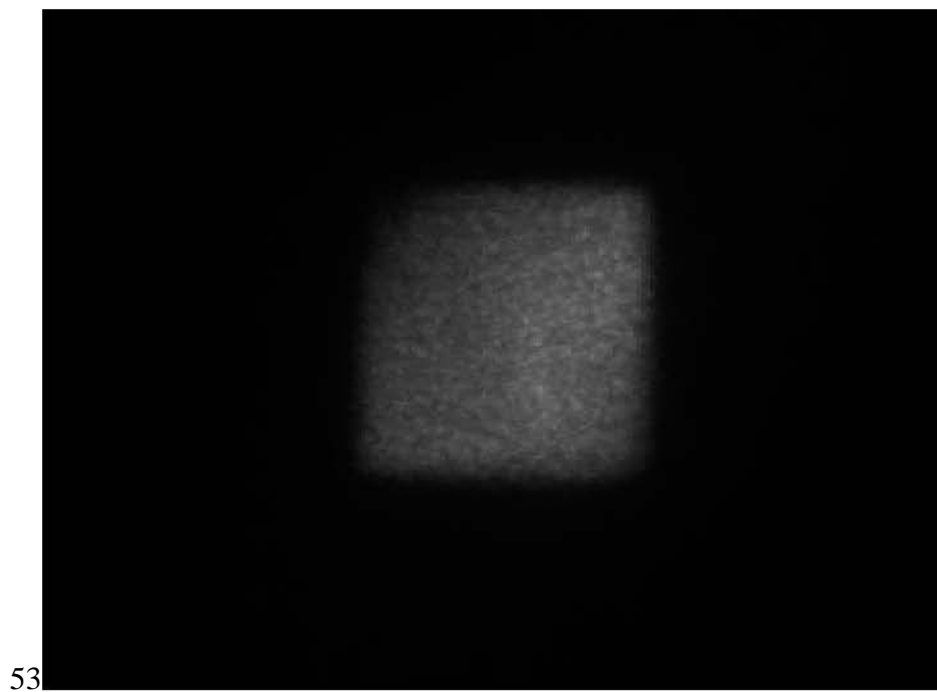
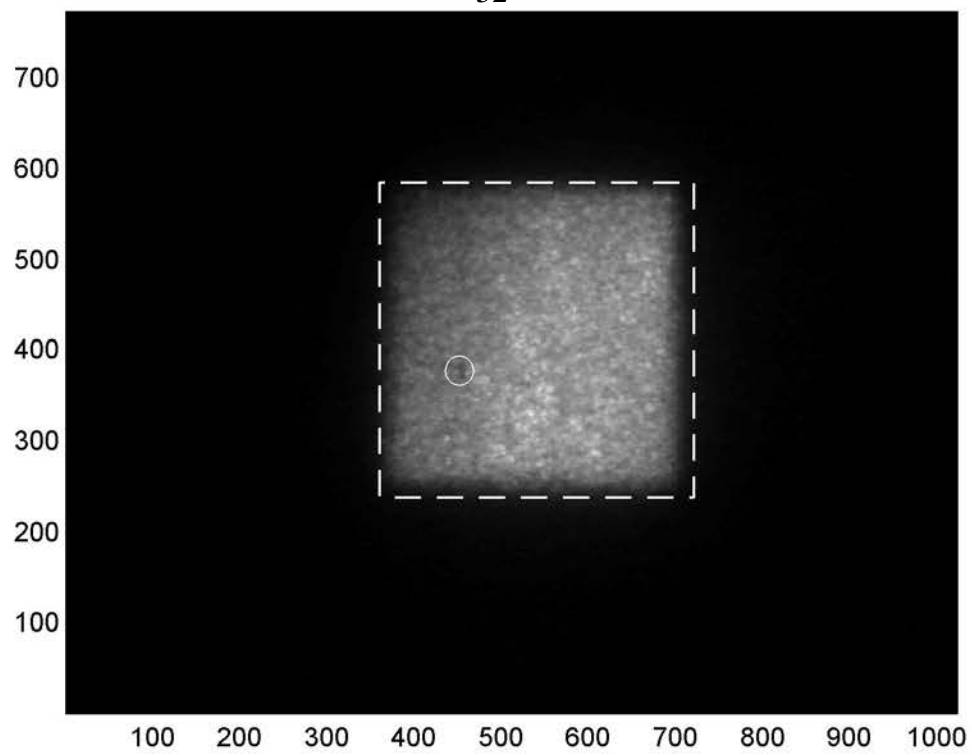




51

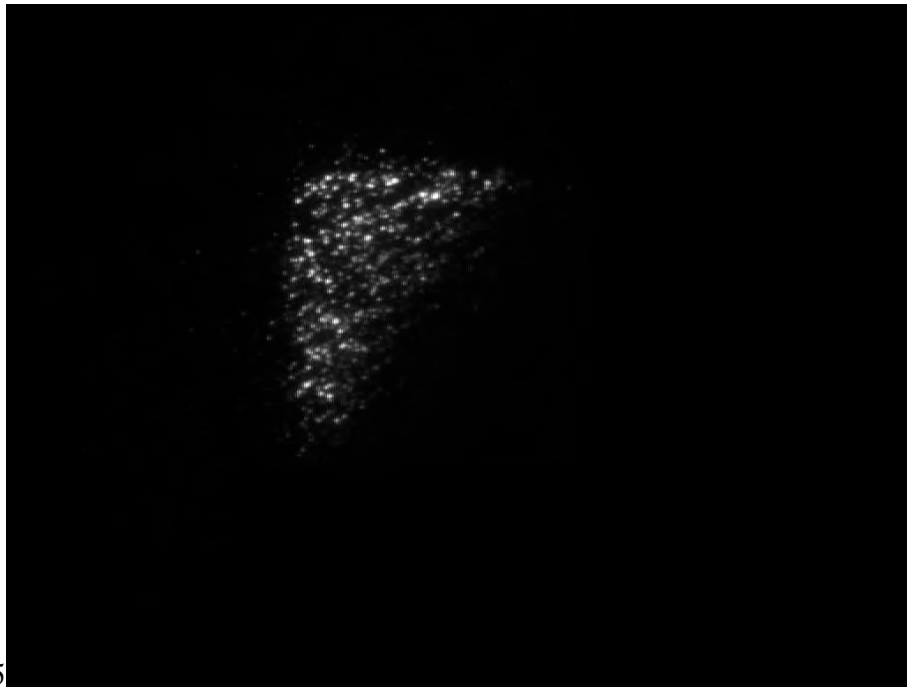


103

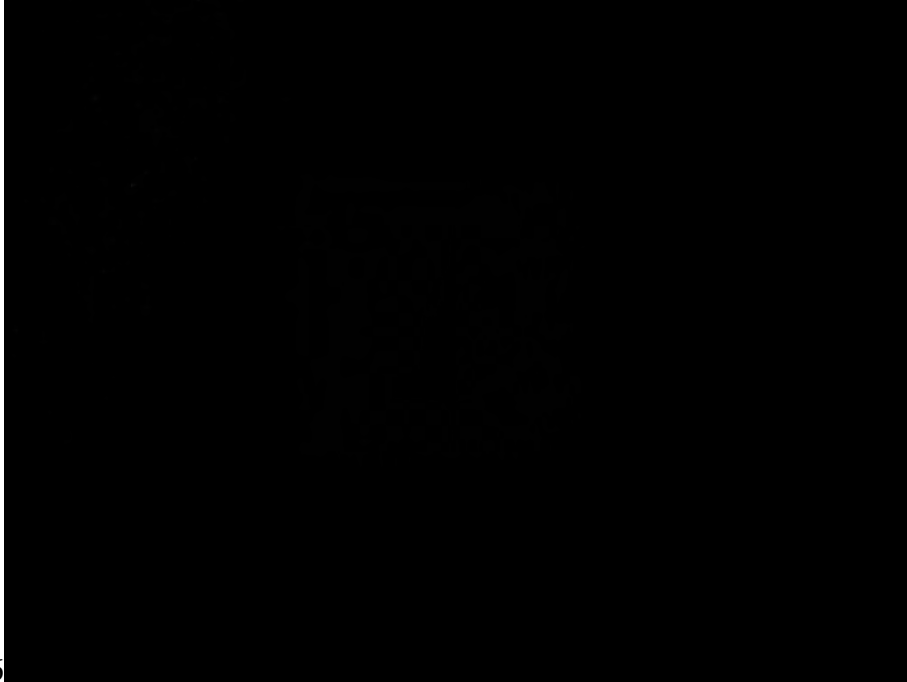




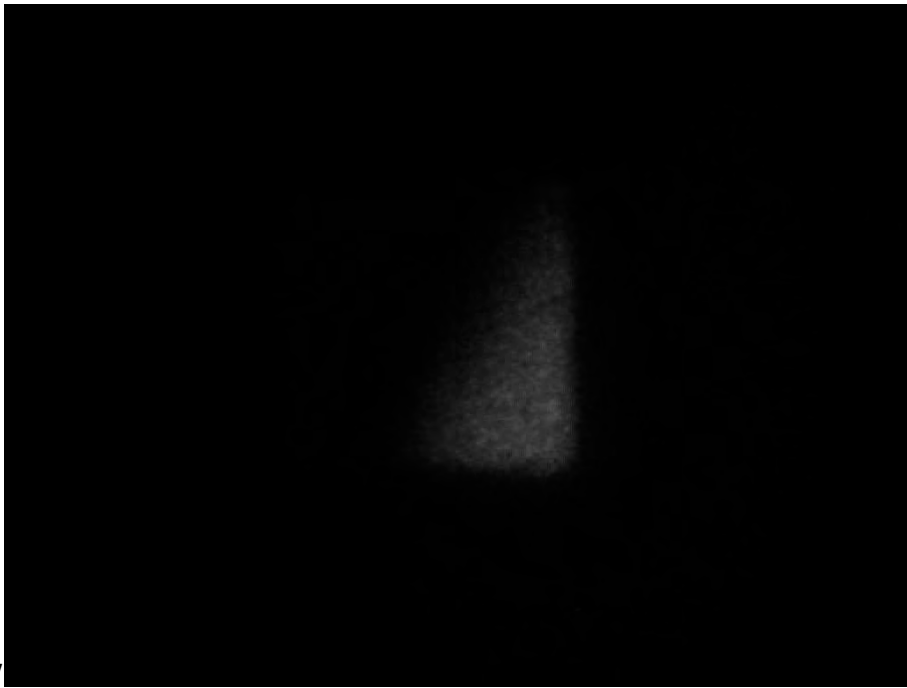
54



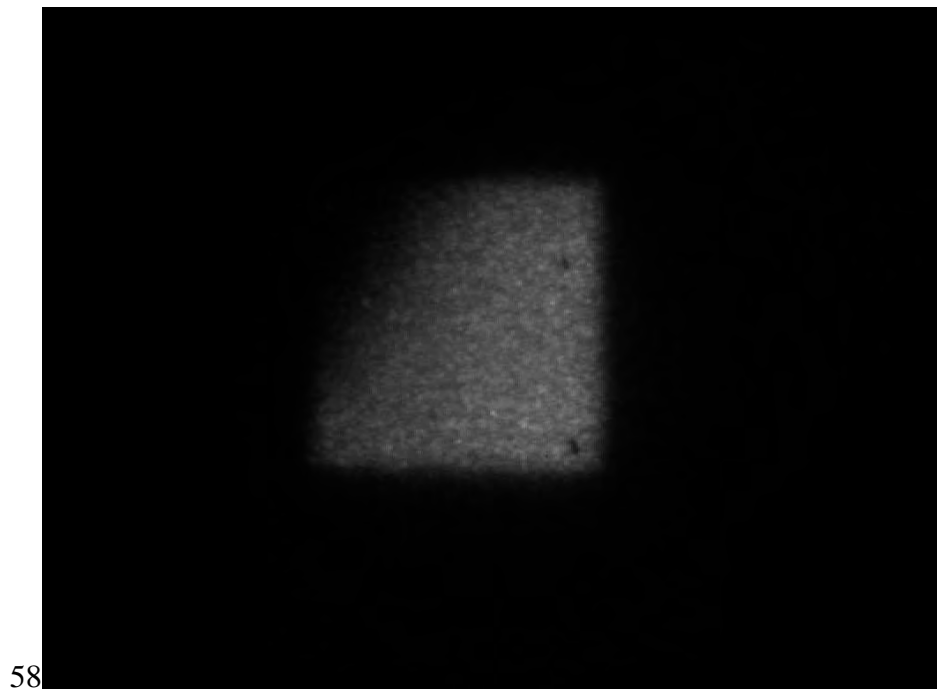
55



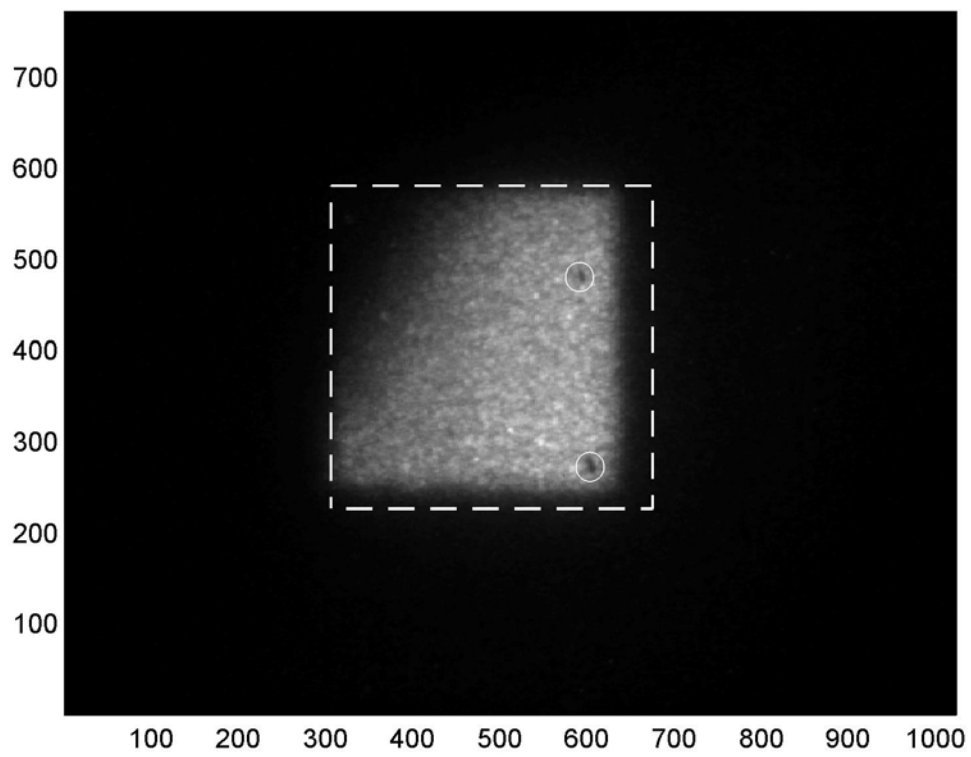
56



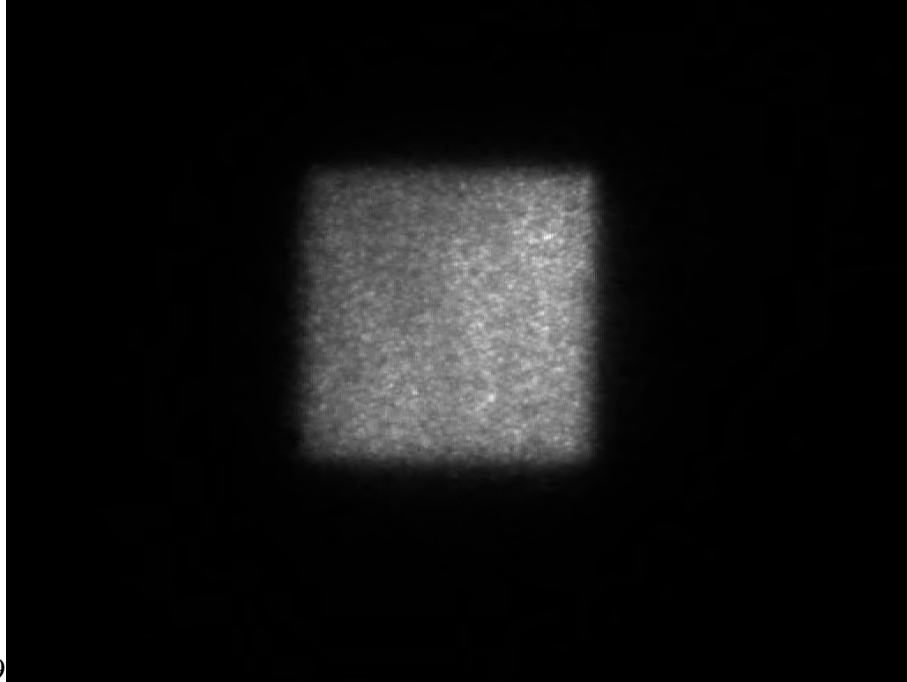
57



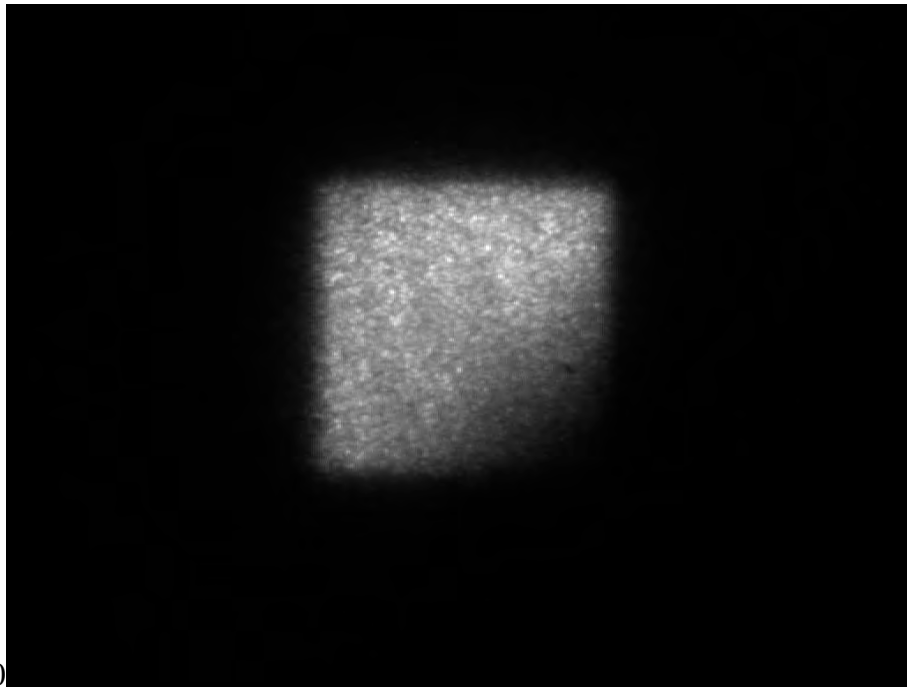
58



107

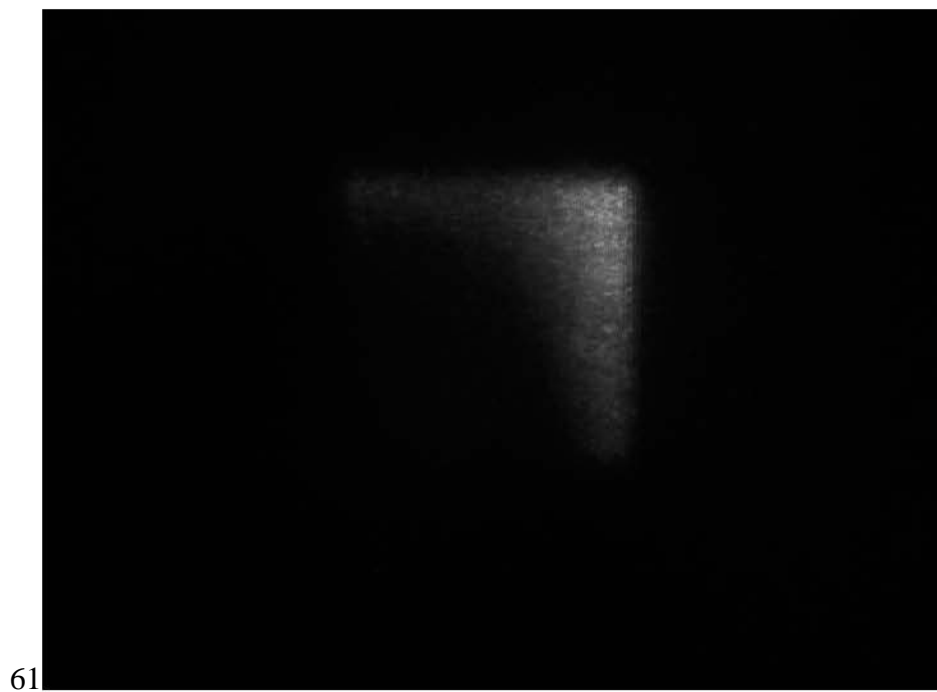
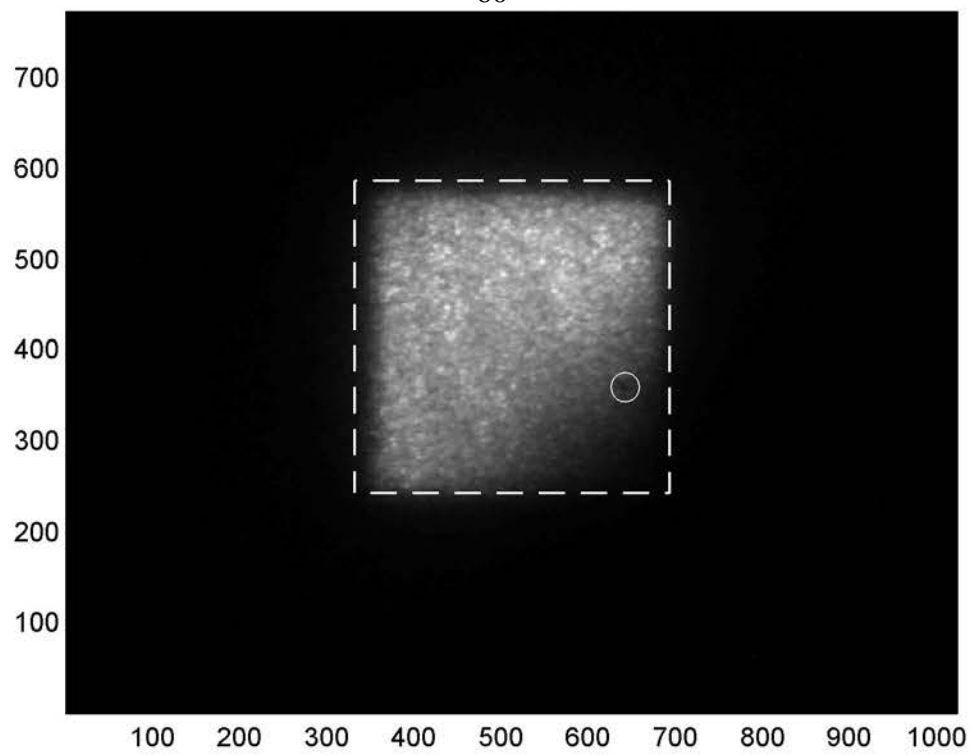


59



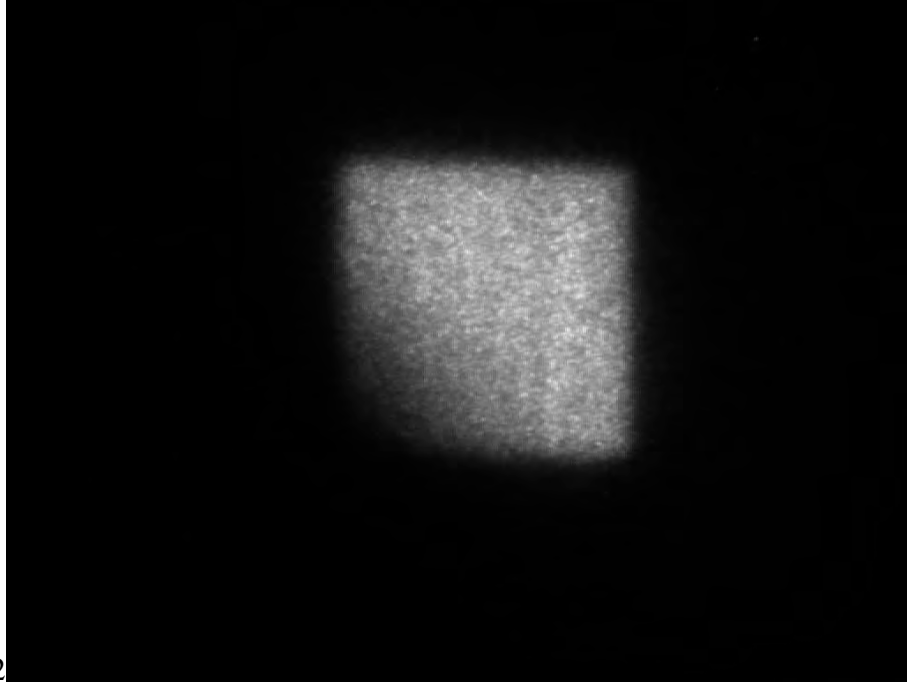
60

60

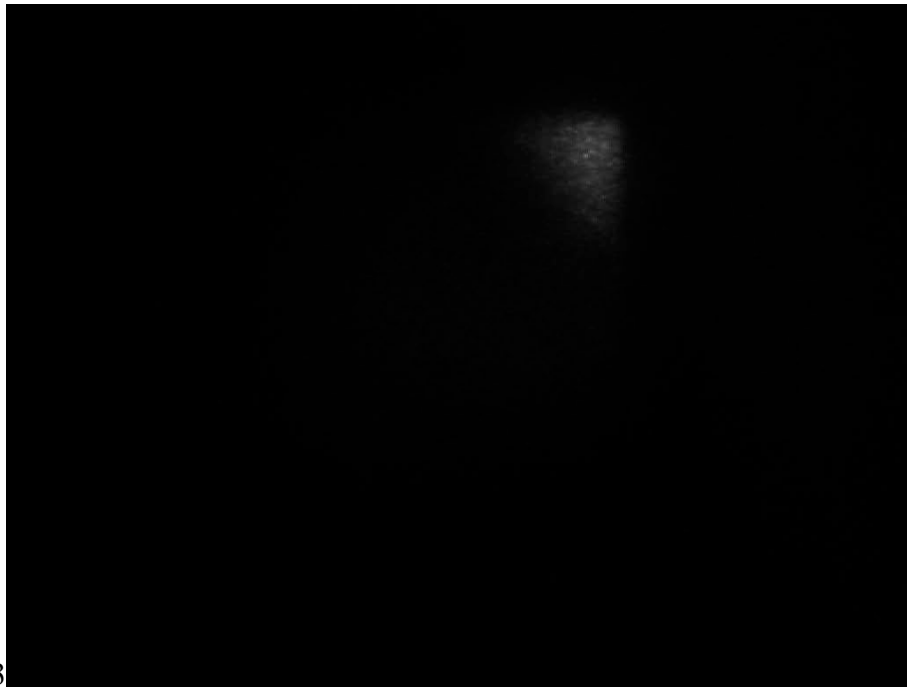


61

109



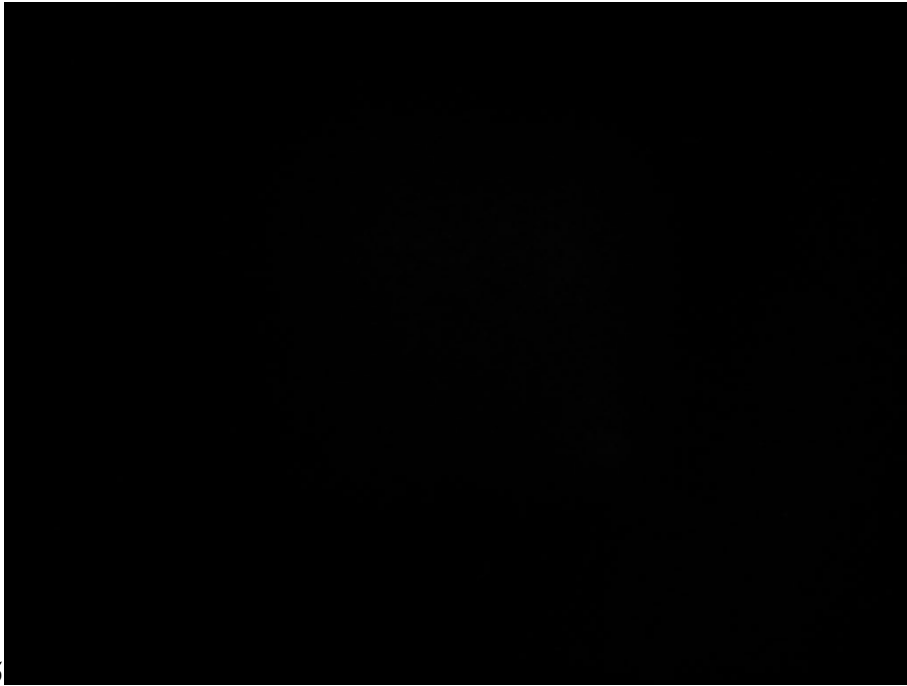
62



63



64

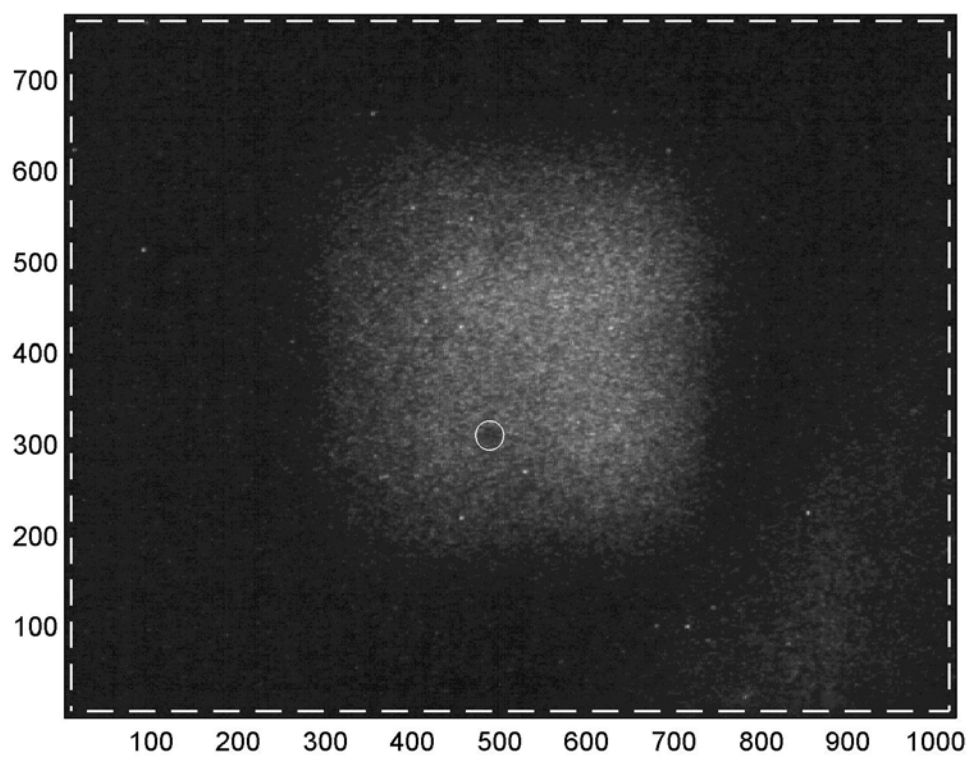


65



66

66

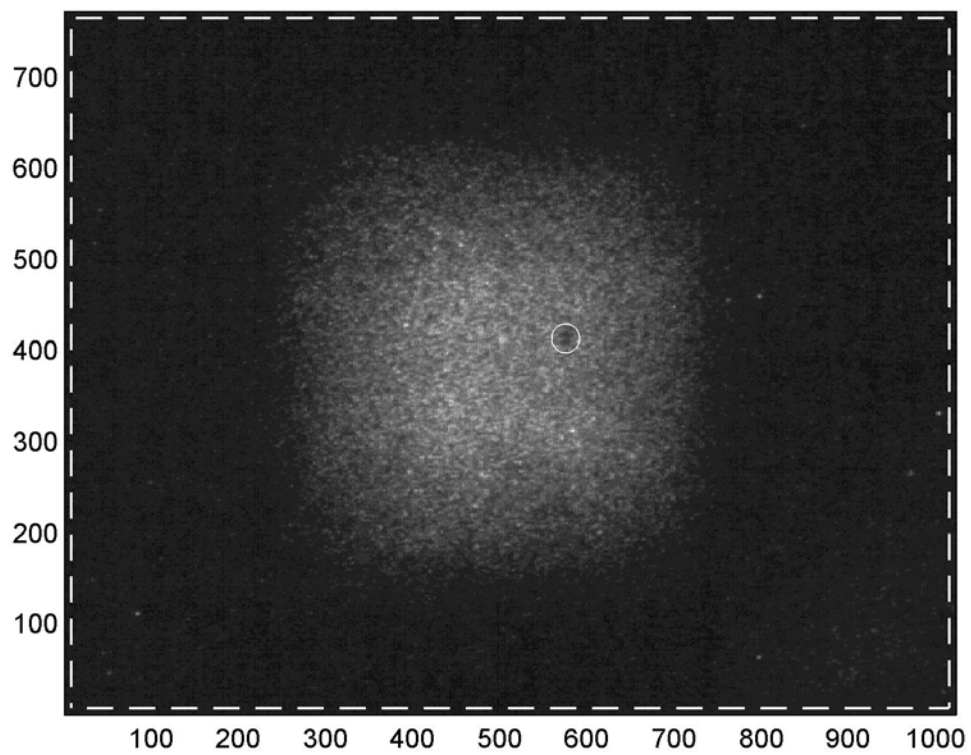


112

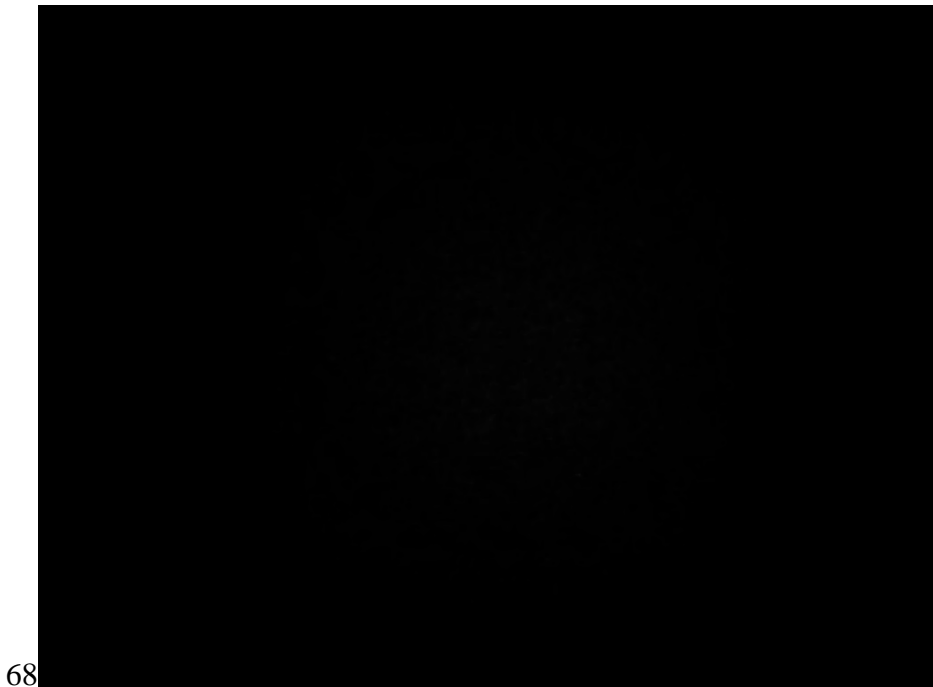


67

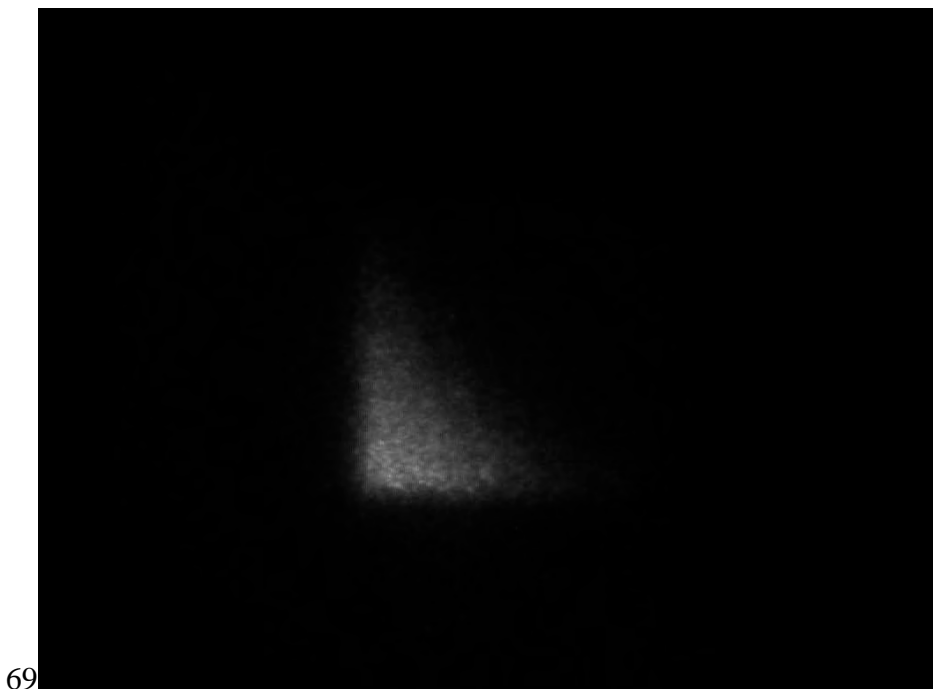
67



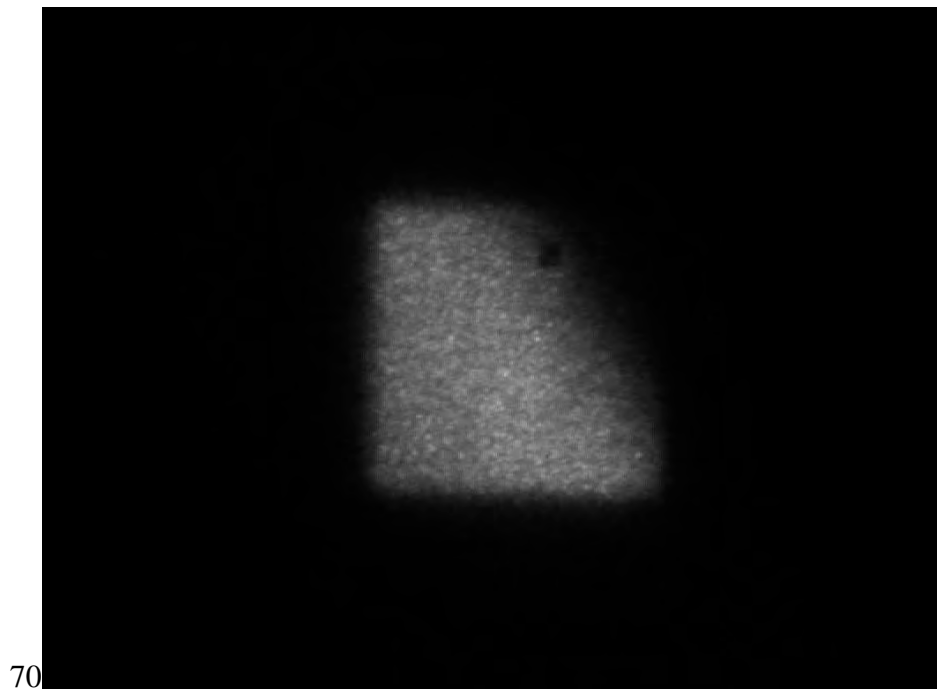
113



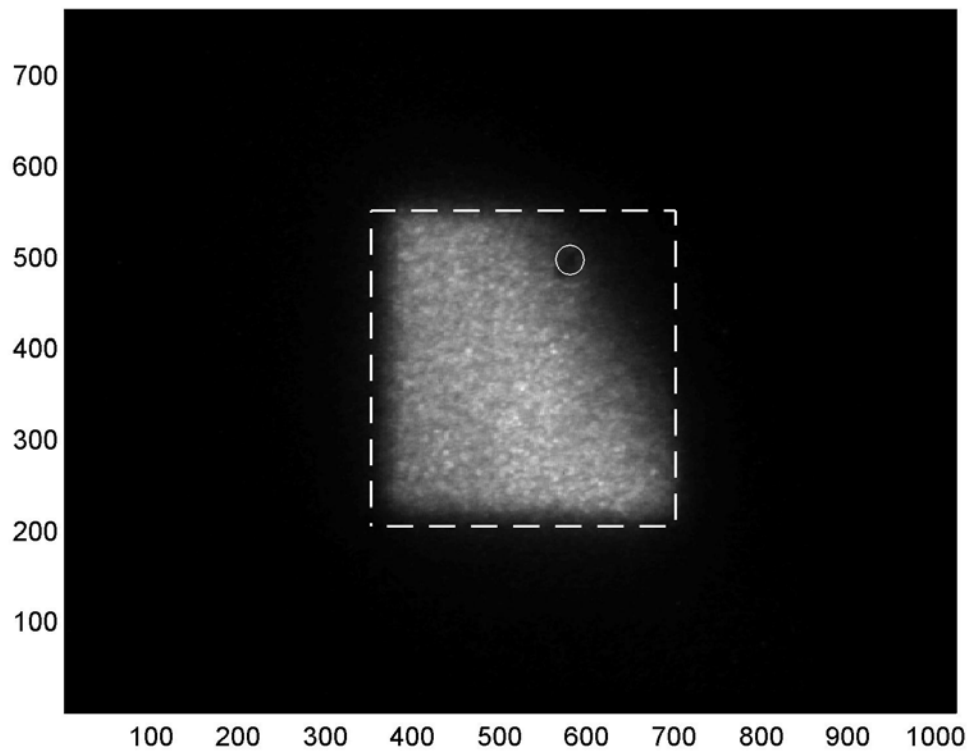
68



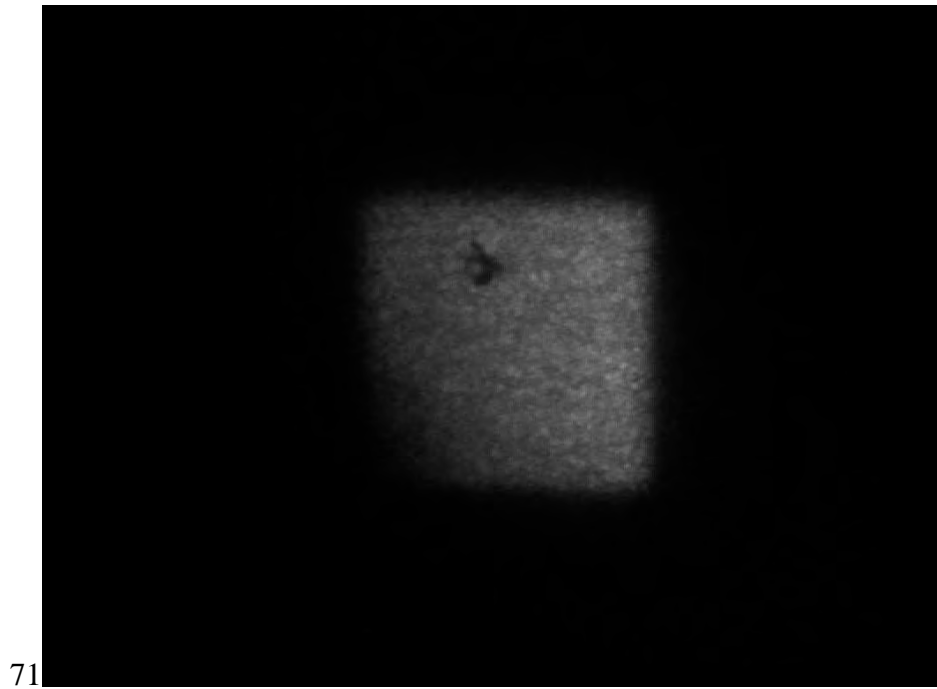
69



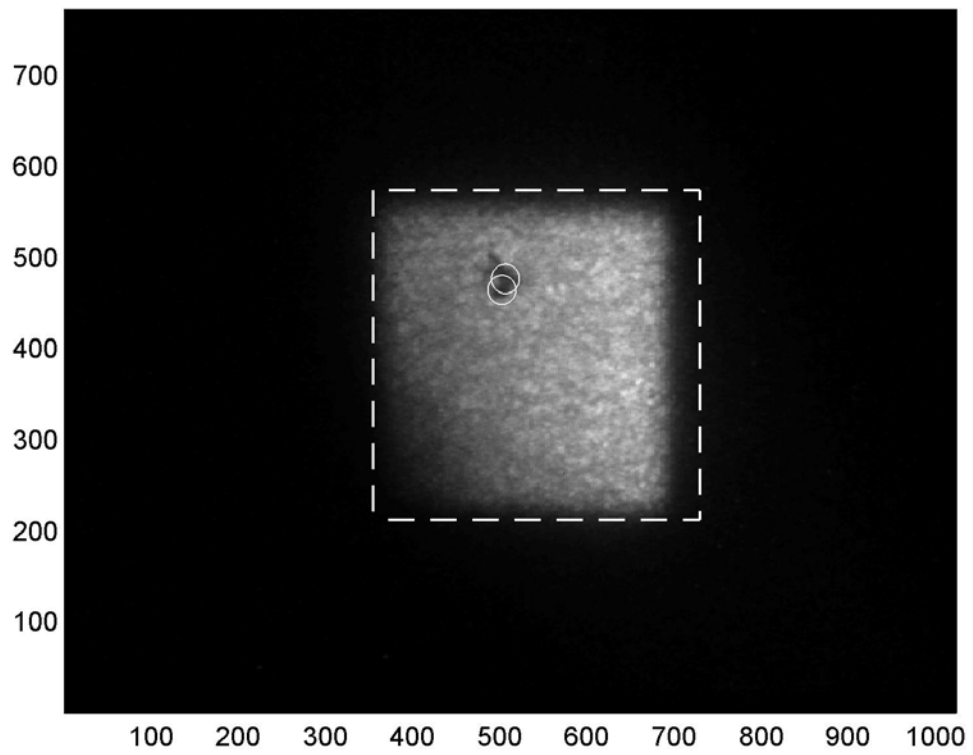
70



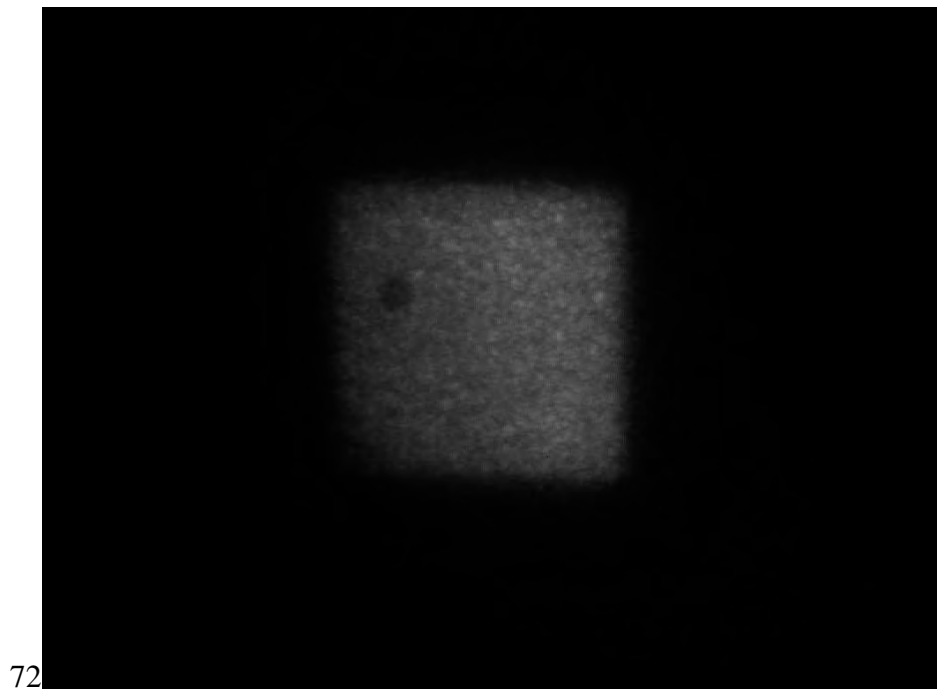
115



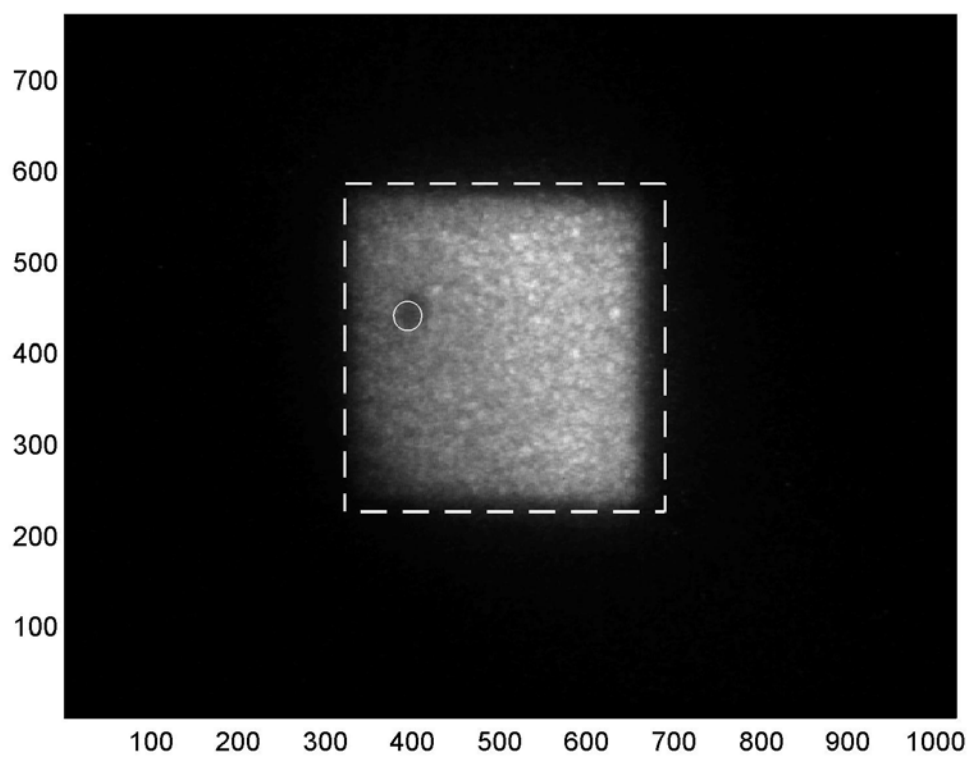
71



116

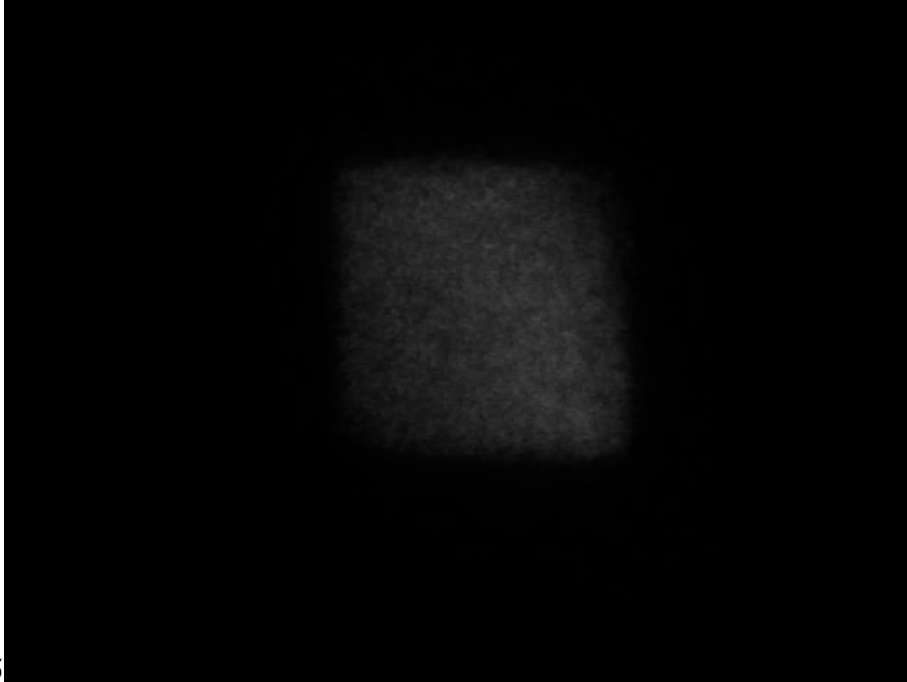


72



117

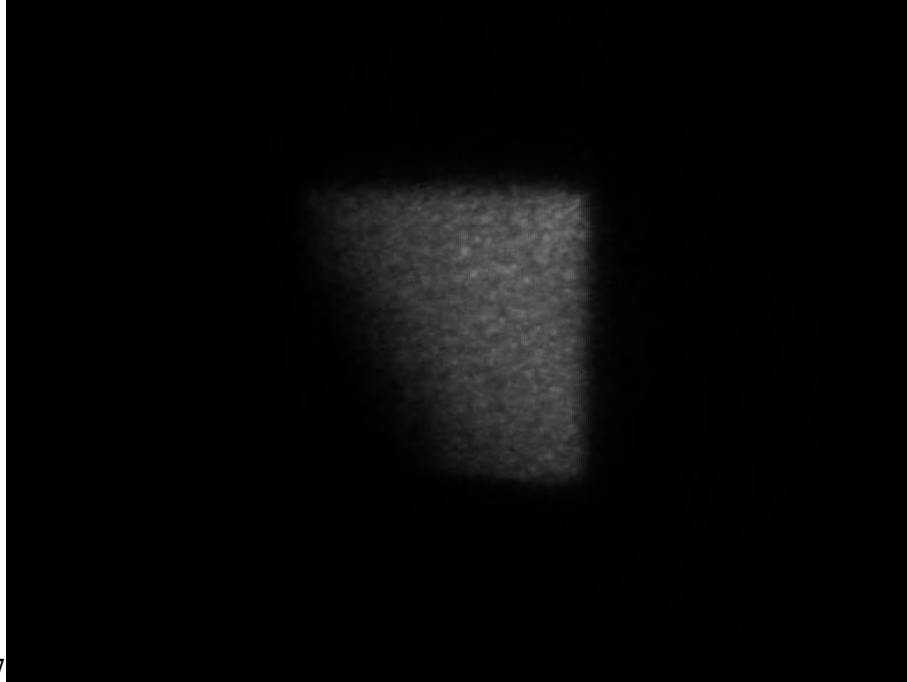




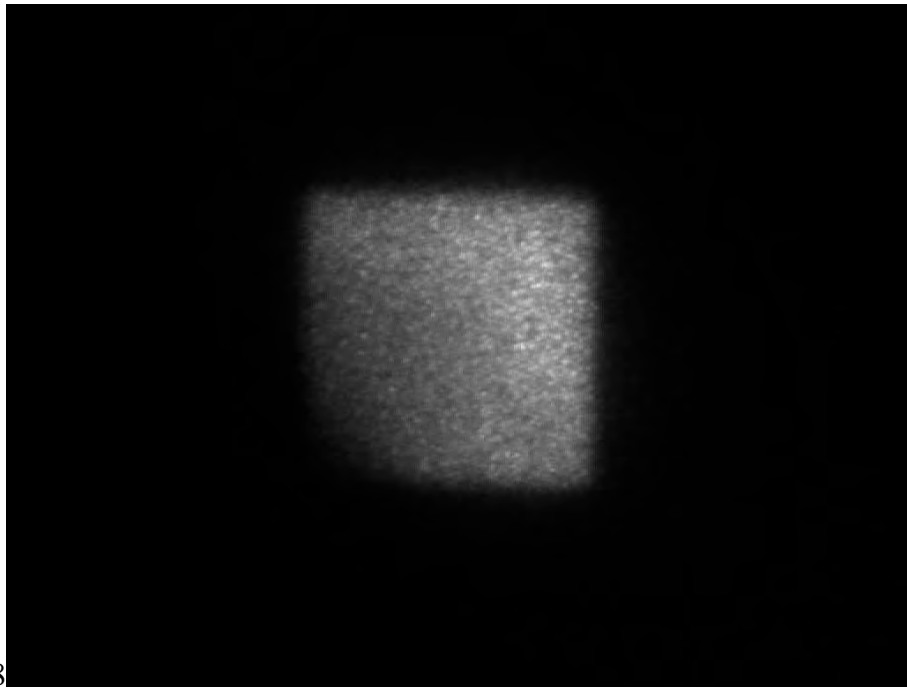
75



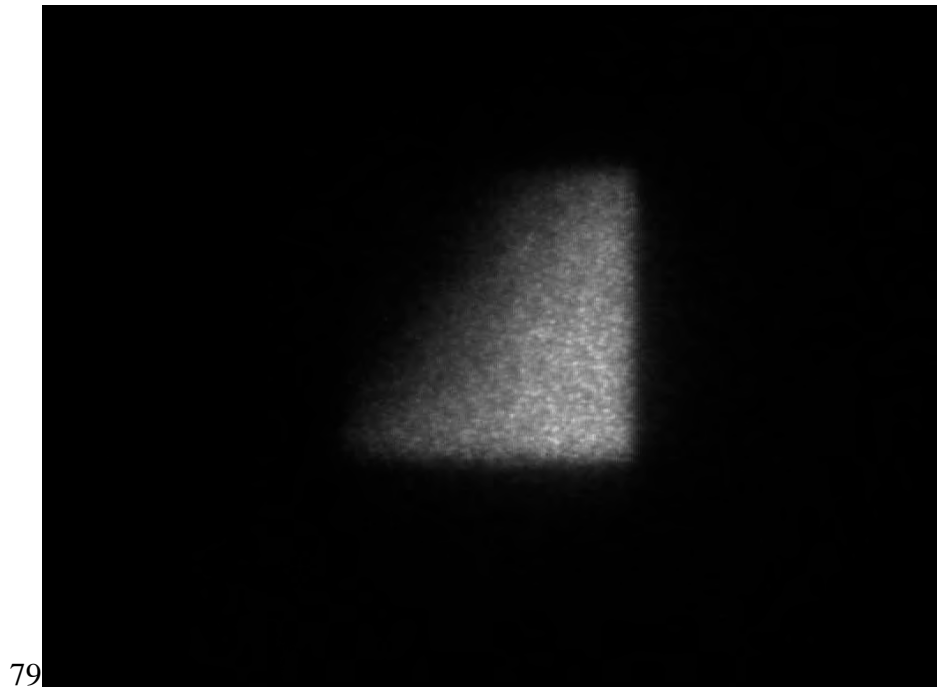
76



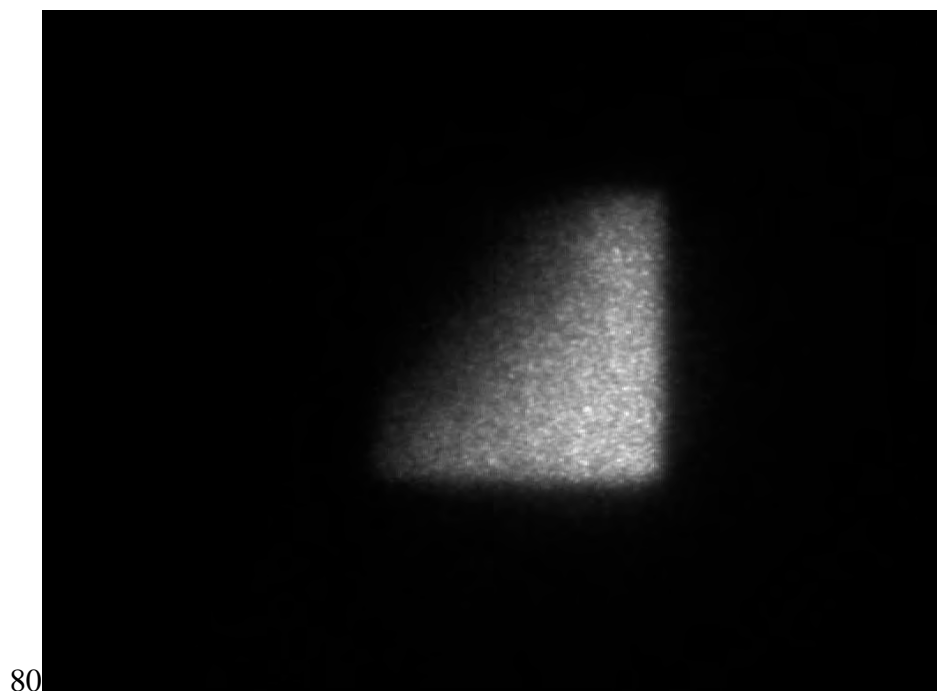
77



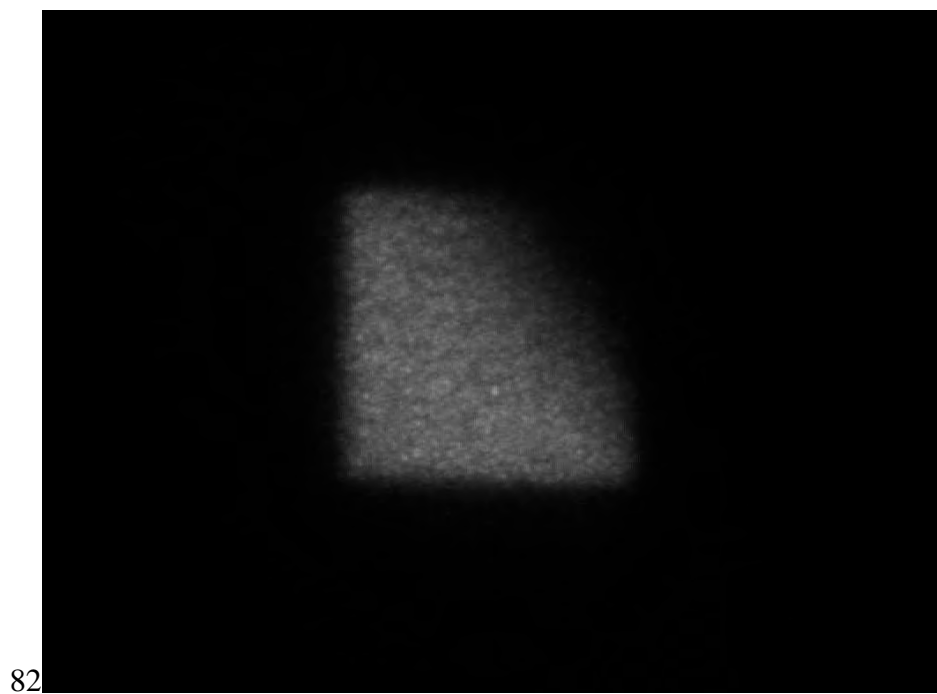
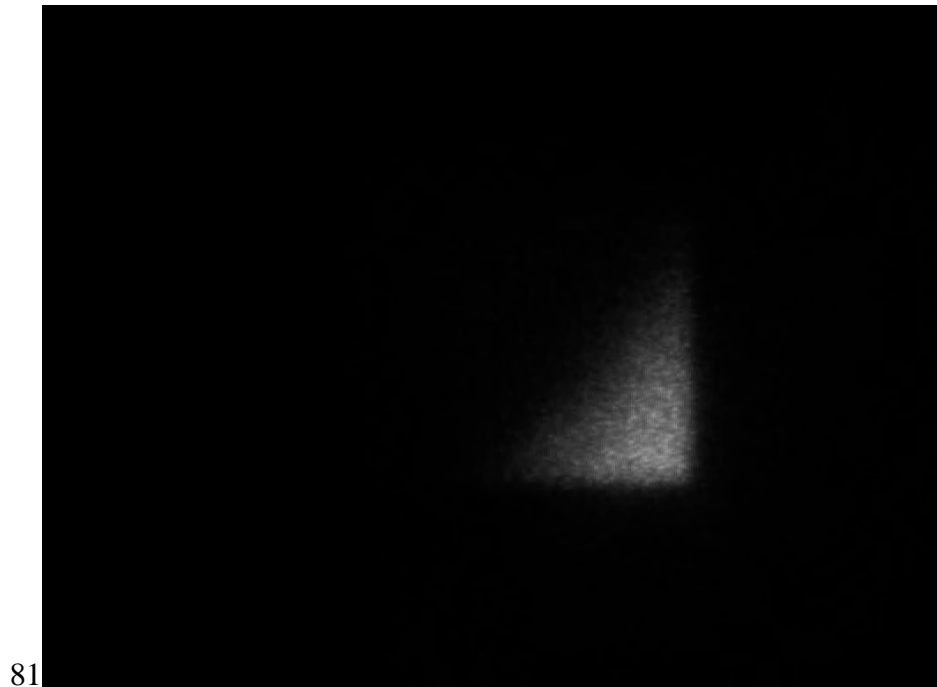
78



79

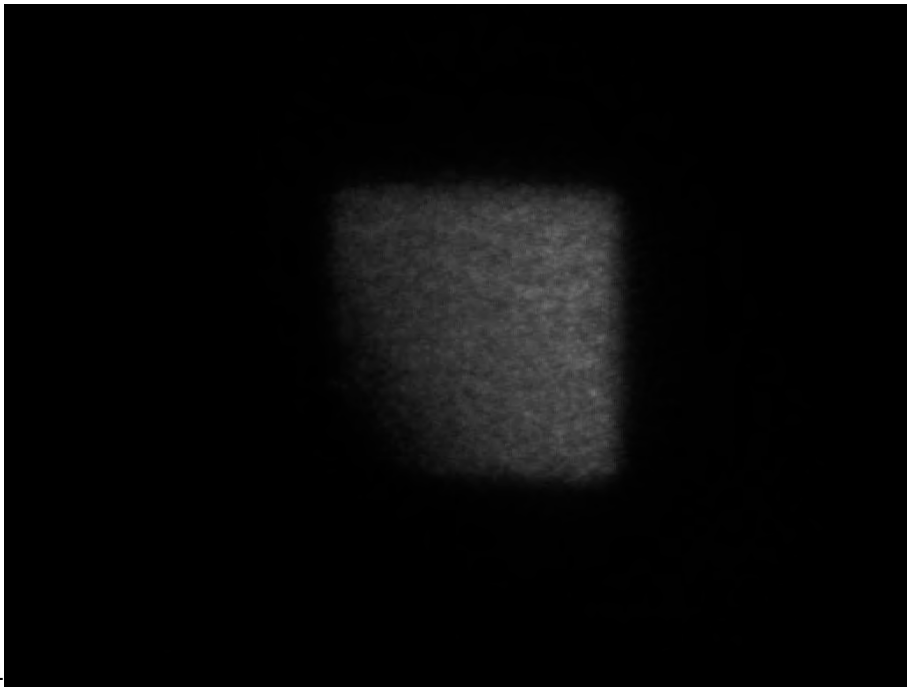


80

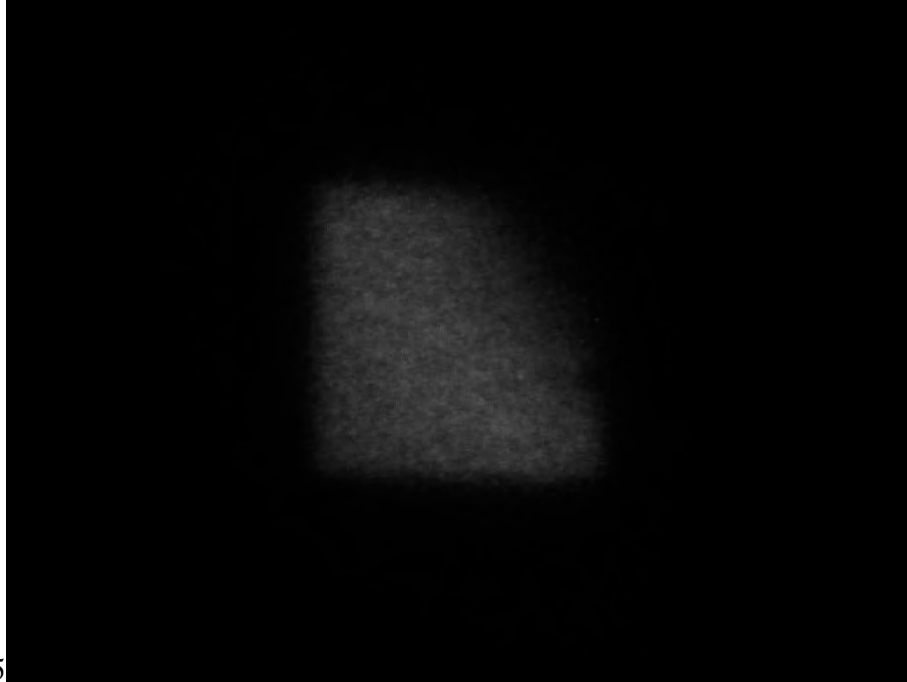




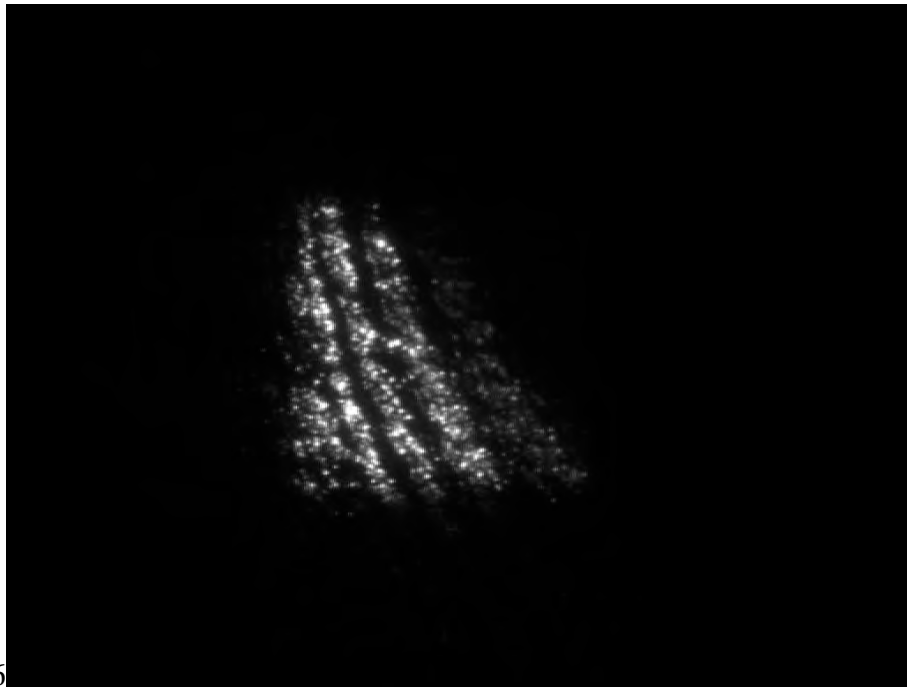
83



84



85



86

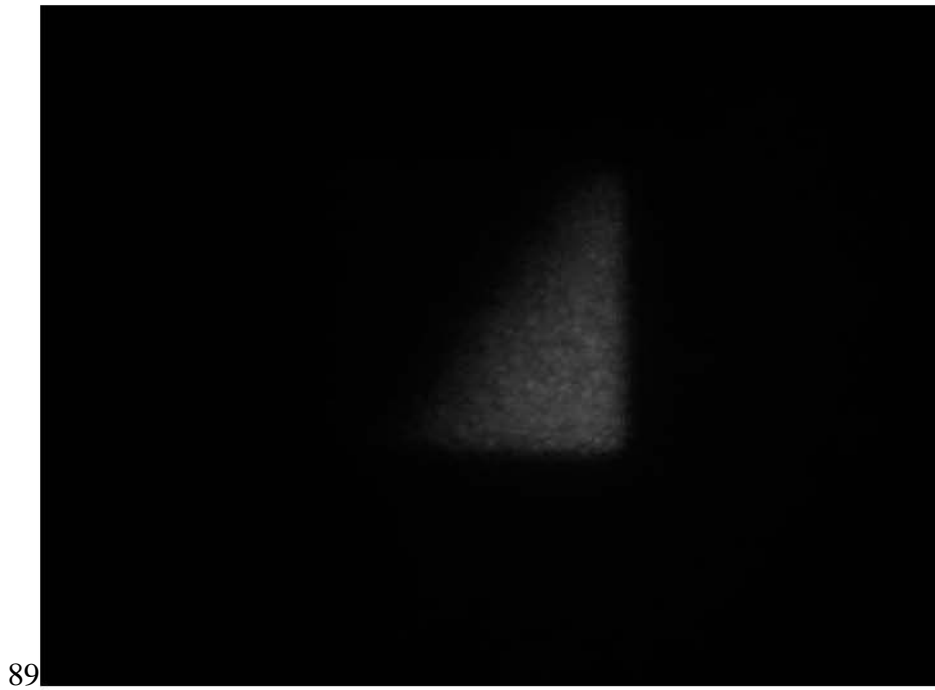
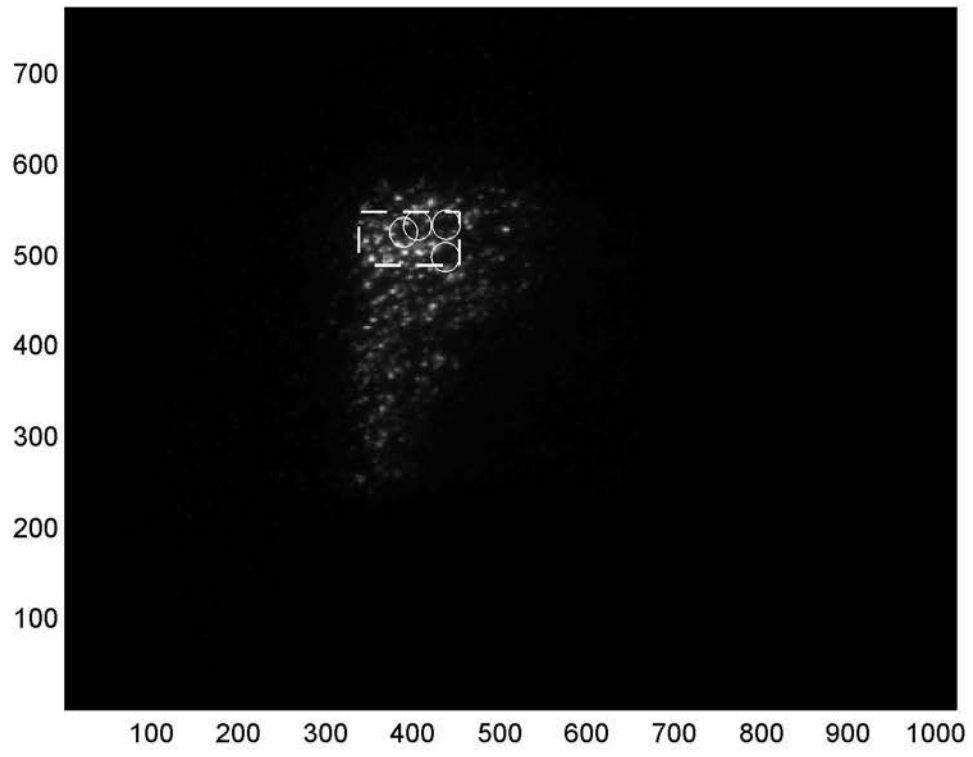


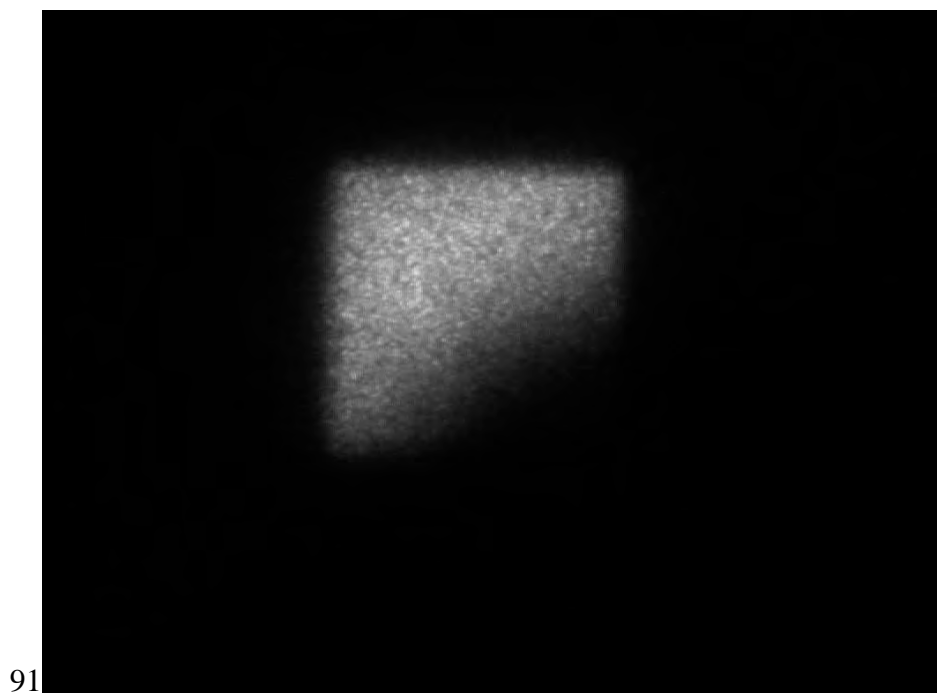
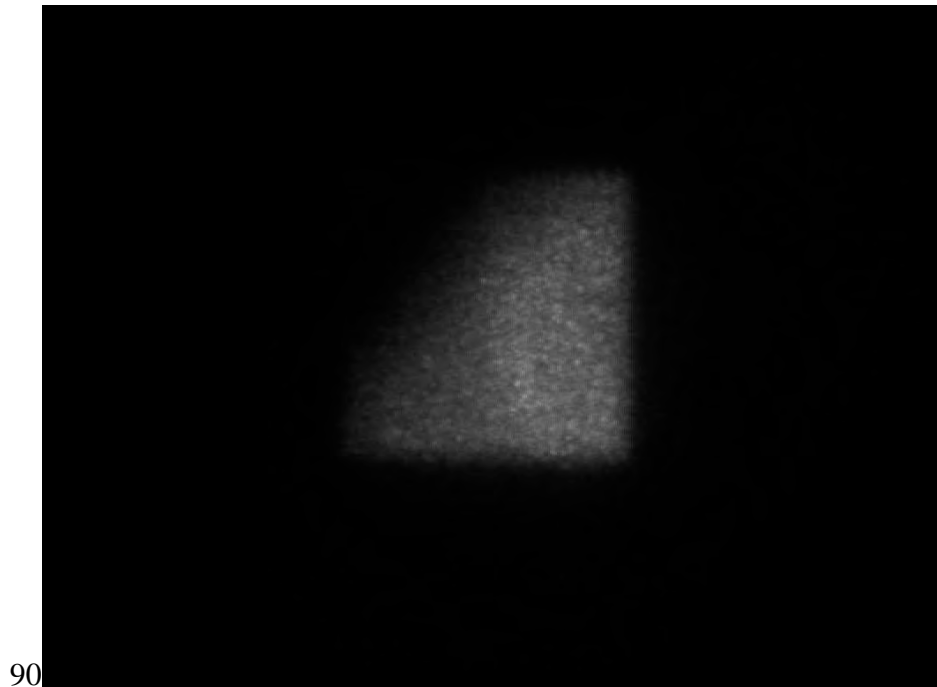
87

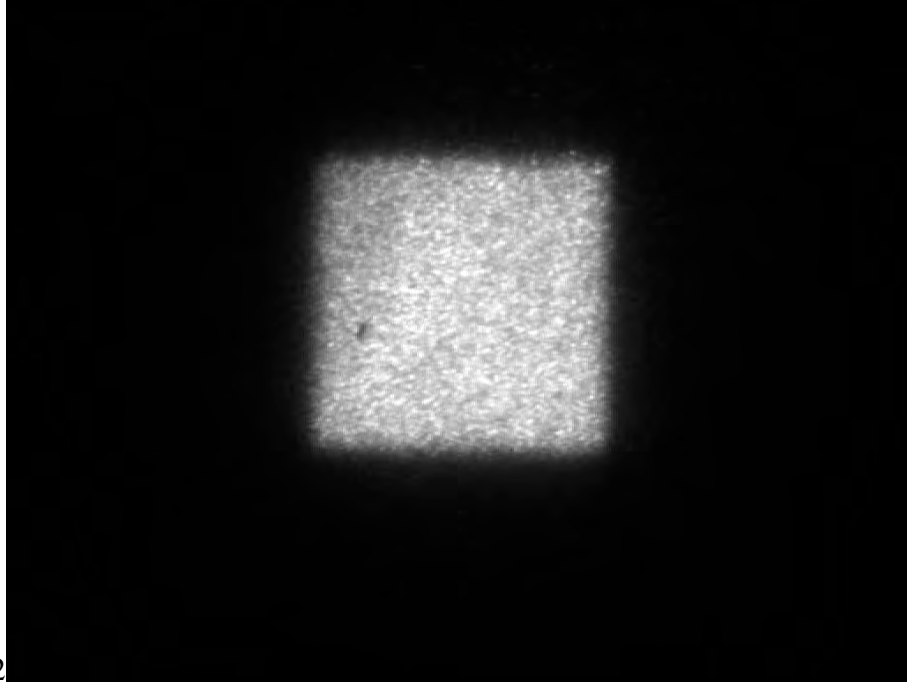


88

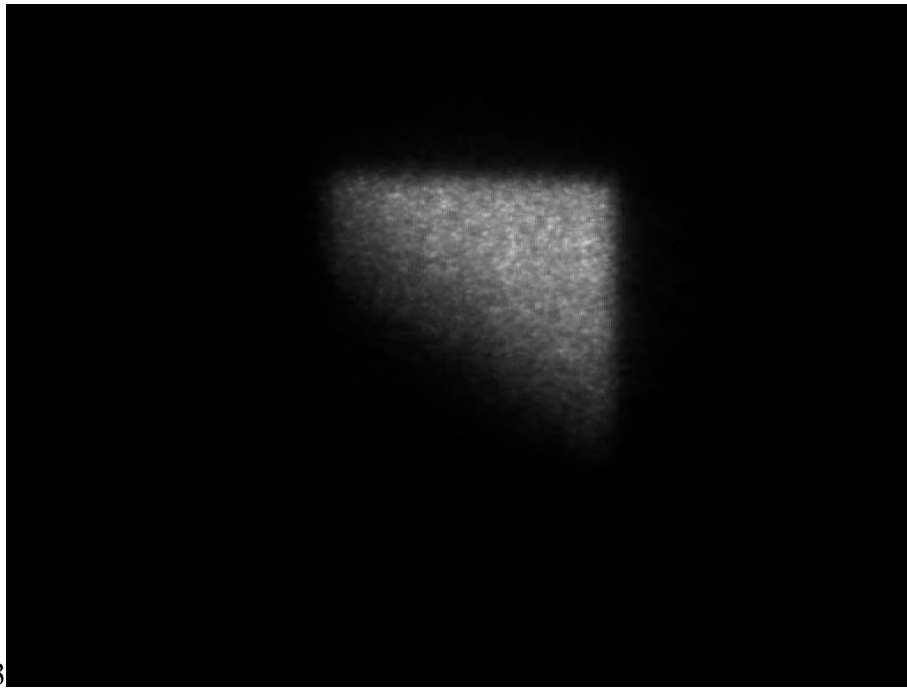
88  
88 pmp







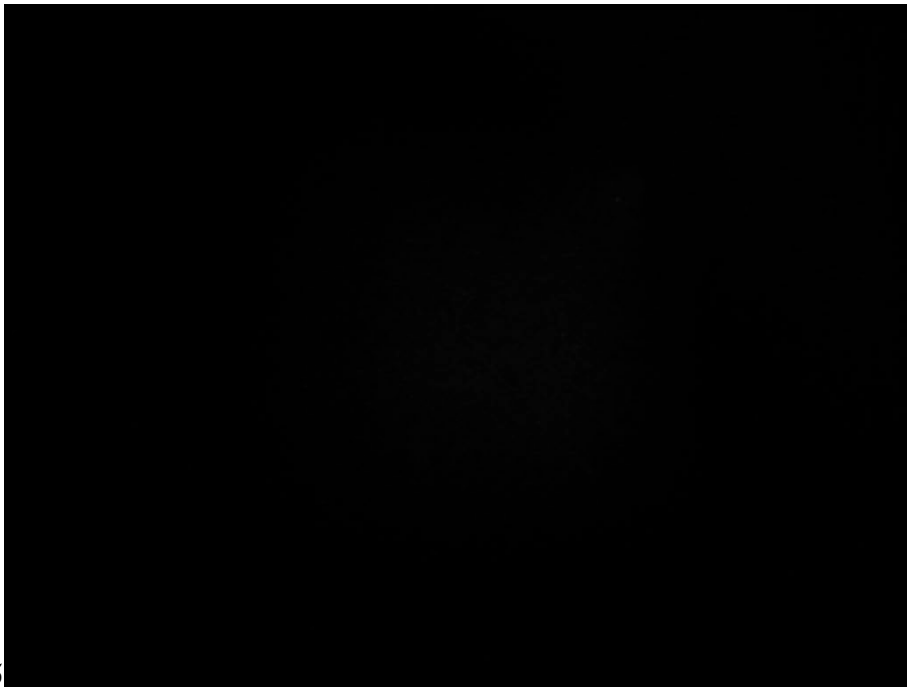
92



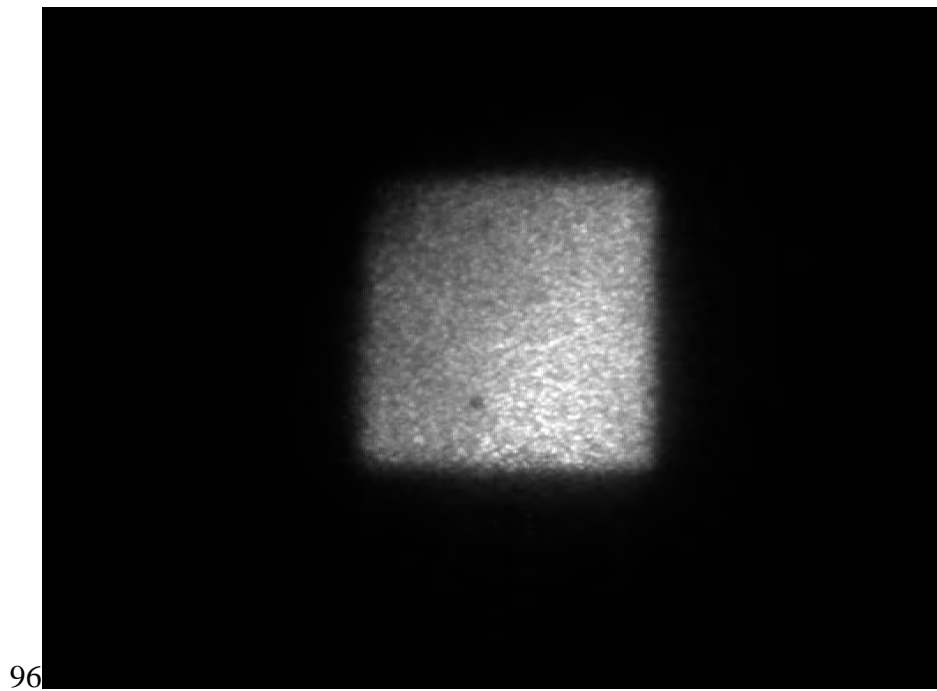
93



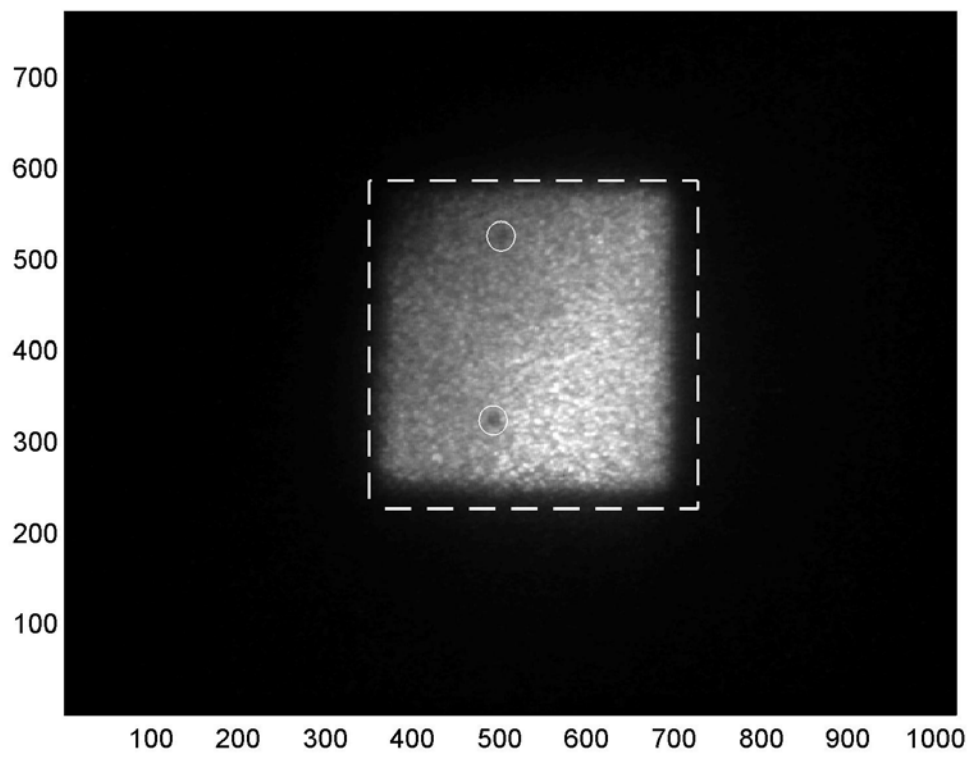
94



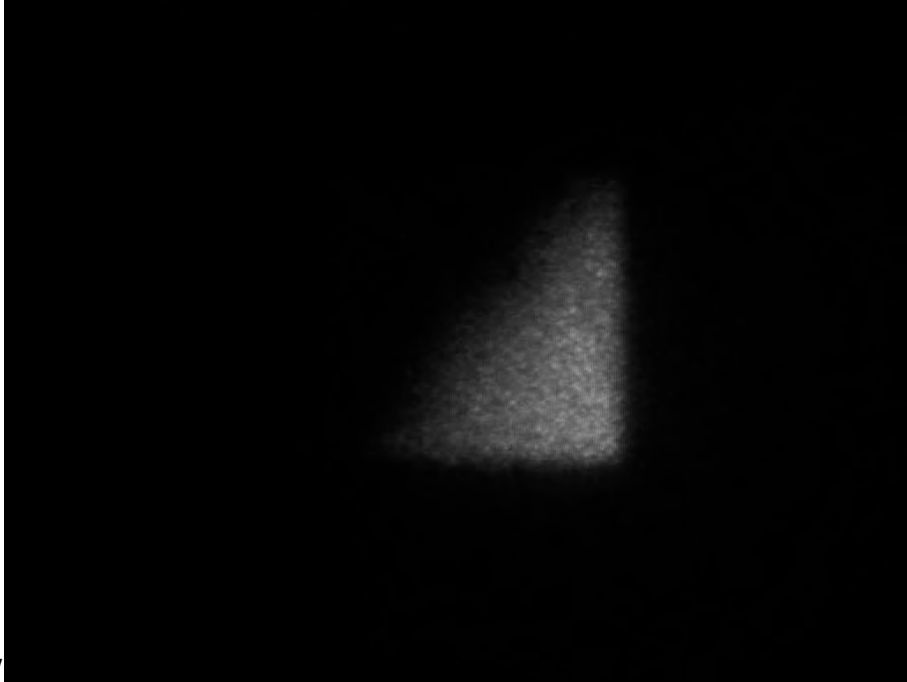
95



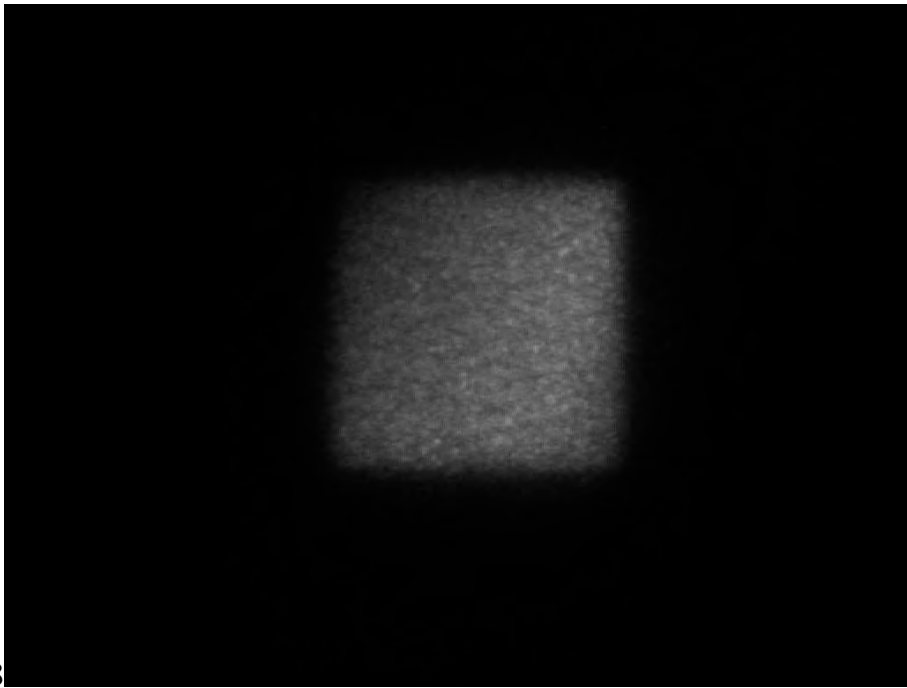
96



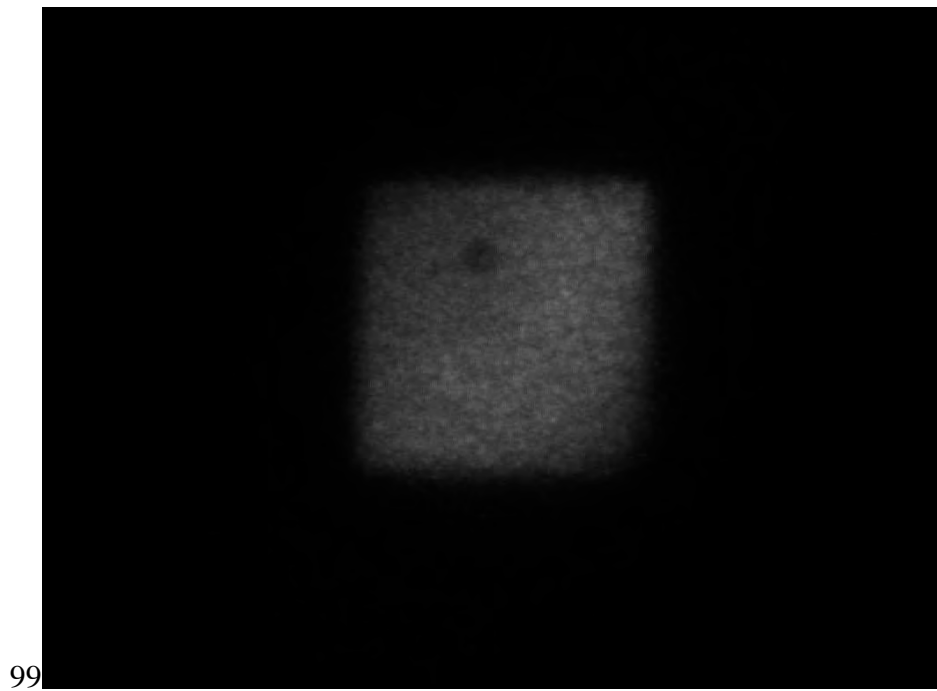
130



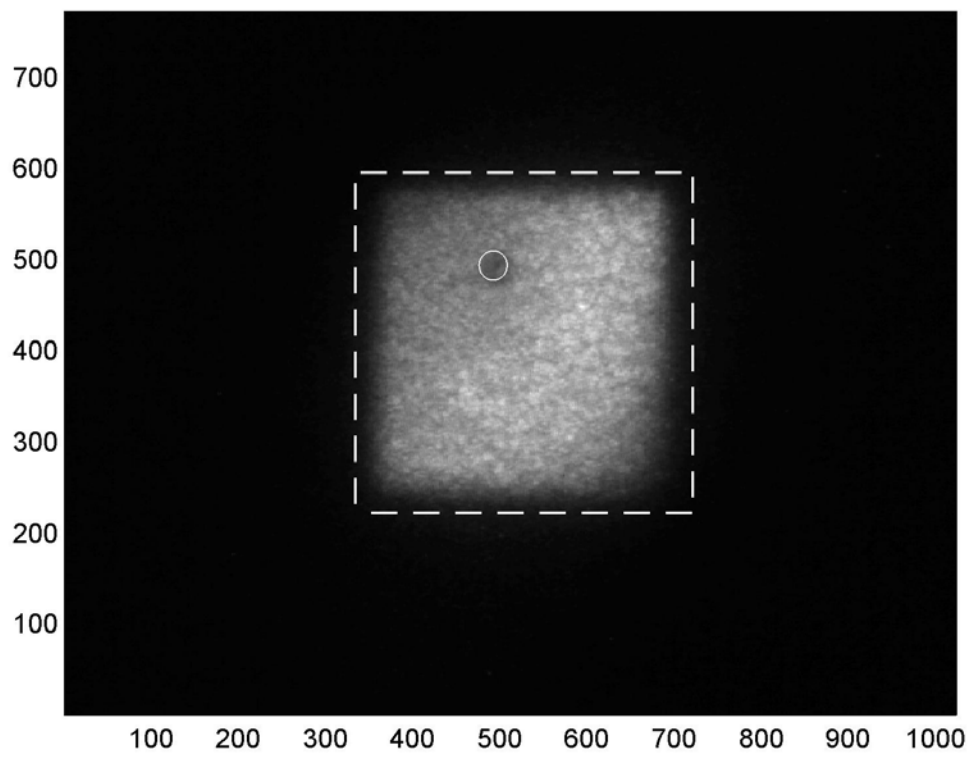
97

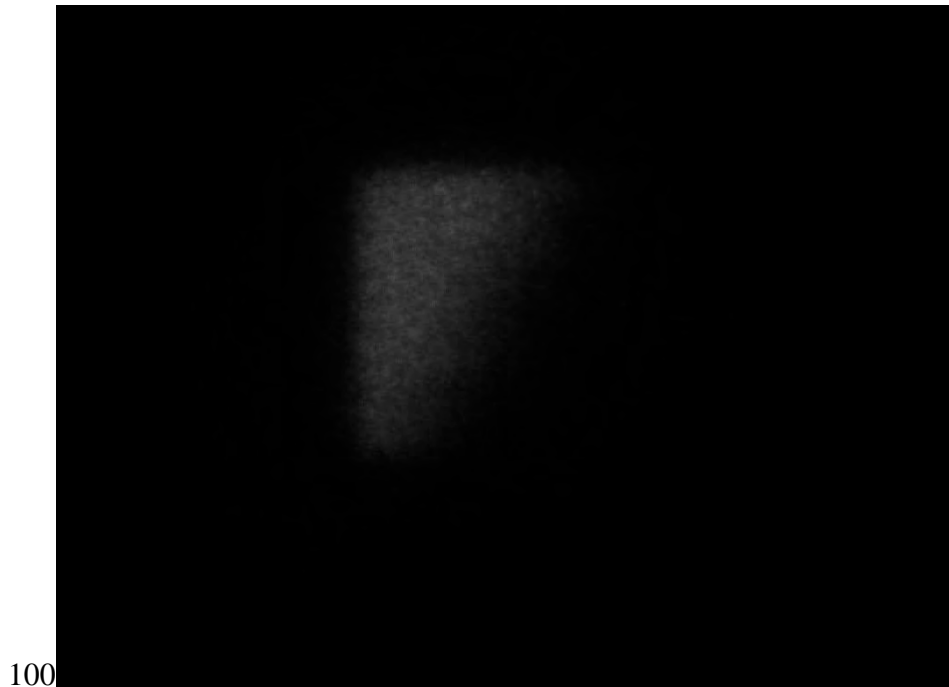


98



99





## B. TEXT FILE

```

p2=0.5, Crit drr=2.2
k=1 1. bmp Obj number=1
    1. 1545    0.0000
    4. 4309    3.2765
k=7 7. bmp Obj number=1
    1. 2953    0.0000
    1. 1737   -0.1216
    1. 4259    0.2521
    2. 0681    0.6423
k=8 8. bmp Obj number=1
    1. 0615    0.0000
    1. 0460   -0.0154
    1. 1606    0.1145
    2. 9346    1.7740
k=21 21. bmp Obj number=1
    1. 0524    0.0000
    1. 4086    0.3562
    1. 2344   -0.1742
    2. 1581    0.9237
k=34 34. bmp Obj number=2
    1. 1565    0.0000
    2. 0954    0.9389
    1. 6618   -0.4336
k=38 38. bmp Obj number=1
    2. 1861    0.0000
    3. 5807    1.3946
k=44 44. bmp Obj number=1
    1. 2062    0.0000
    5. 3953    4.1891
k=45 45. bmp Obj number=1
    1. 0048    0.0000
    1. 0987    0.0938
    1. 2229    0.1242

```

	4. 7619	3. 5390	
k=46	46. bmp	Obj number=1	
	1. 1022	0. 0000	
	2. 3152	1. 2130	
k=51	51. bmp	Obj number=1	
	1. 6715	0. 0000	
	3. 6163	1. 9448	
k=52	52. bmp	Obj number=1	
	1. 0813	0. 0000	
	1. 9145	0. 8332	
k=58	58. bmp	Obj number=2	
	1. 1603	0. 0000	
	1. 7343	0. 5740	
	1. 3728	-0. 3615	
k=60	60. bmp	Obj number=1	
	1. 0552	0. 0000	
	1. 8502	0. 7951	
k=66	66. bmp	Obj number=1	
	1. 1735	0. 0000	
	1. 7976	0. 6241	
k=67	67. bmp	Obj number=1	
	1. 0655	0. 0000	
	1. 9691	0. 9036	
k=70	70. bmp	Obj number=1	
	1. 2219	0. 0000	
	8. 0425	6. 8206	
k=71	71. bmp	Obj number=2	
	1. 4562	0. 0000	
	6. 5333	5. 0771	
	1. 1022	-5. 4311	
k=72	72. bmp	Obj number=1	
	1. 0449	0. 0000	
	4. 2805	3. 2356	
k=96	96. bmp	Obj number=2	
	1. 1767	0. 0000	
	1. 7511	0. 5744	
	2. 0118	0. 2607	
k=99	99. bmp	Obj number=1	
	1. 0330	0. 0000	
	4. 6490	3. 6160	

## LIST OF REFERENCES

- Abbass, D. K., and Mather, R., 2008: The history of the HMS Cerberus and HMS Lark. [Available online at <http://oceanexplorer.noaa.gov/explorations/08auvfest/background/history/history.html>.]
- Almquist, B., 2009: Assault breaching technologies update. *MINWARA Spring 2009 regional Conference on Mine Warfare—“Home” and “Away” Game Challenges*, May 18–21, 2009.
- Almquist, B., 2012: Rapid Clearance of Large Areas of Mines. *The Menneken Lecture Series Naval Postgraduate School*, Monterey, CA.
- Avery, J., 1998: The naval mine threat to U.S. surface forces. *Surface Warfare*, 4–9.
- Cian, C. M., Zurawski, W. C., Dobeck, G. J., and Weilert, D. R., 2003: Real-time performance of fusion algorithms for computer aided detection and classification of bottom mines in the littoral environment, *OCEANS 2003. Proceedings (Vol.2)*, 22–26 September 2003, **2685**, 1119–1125.
- Chu, P. C., and Vares, N. A., 2004: Uncertainty in shallow sea acoustic detection due to environmental variability. *U.S. Navy Journal of Underwater Acoustics*, 54, 347–367.
- Commander Naval Meteorology and Oceanography Command, 1999: *Fleet Oceanographic and Acoustic Reference Manual (RP-33)*. Naval Oceanographic Office.
- Dobeck, G. J., Hyland, J. C., and Smedley, L., 1997: Automated Detection /Classification of Sea Mines in Sonar Imagery, Detection and Remediation Technologies for Mines and Minelike Targets II, *SPIE*, **3079**, 90–110.
- Fawcett, John A.; and Myers, Vincent L., 2005: *Computer-aided detection and classification of minelike objects*. Defense R&D Canada—Atlantic Technical Memorandum, 61.
- Harbaugh, J. K.; Sternlicht, D. D.; Putney, A.; Tinkle, M. D.; Lavelly, E. M.; Sternlicht, D. D.; Putney, A.; Tinkle, M. D.; and Lavelly, E. M., 2006: Acoustic modeling for sea-mine CAD/CAC development. *Oceans Conference 2005 MTS/IEEE, Washington D.C.*, 850–854.
- Joint Chiefs of Staff, 1999: *Joint Doctrine for barriers, obstacles, and mine warfare, joint publication 3–15*, 136 pp.

- Melia, T. M., 1991: "*Damn the torpedoes*": A short history of U.S. naval mine countermeasures, 1777–1991. Naval Historical Center, 209 pp.
- National Research Council, 2001: *Naval Mine Warfare: Operational and Technical Challenges for Naval Forces*. Committee for Mine Warfare Assessment, Naval Studies Board, 218 pp.
- Naval Surface Warfare Center, 2007: *Mine Countermeasures (MCM) Theory Primer*, Naval Surface Warfare Center.
- Ocean Studies Board, National Research Council, 2000: *Oceanography and Minewarfare*, Ocean Studies Board, Commission on Geosciences, Environment, and Resources, National Research Council, **112**, 42–48.
- PEO LMW, 2009: 21<sup>st</sup> Century U.S. Navy Mine Warfare: Ensuring Global Access and Commerce. [Available online at [http://www.navy.mil/n85/miw\\_primer-june2009.pdf](http://www.navy.mil/n85/miw_primer-june2009.pdf)]
- PEO LCS, 2011: Coastal Battlefield Reconnaissance and Analysis (COBRA) [Fact sheet]. [Available online at <http://acquisition.navy.mil/content/download/7894/36458/version/1/file/080811+cobra+v3.pdf>.]
- Truver, S. C., 2008: Mines and underwater IEDS in U.S. ports and waterways: context, threats, challenges, and solutions. *Naval War College Review*, **61**, no. 1, 106–127.
- Watts, A. J., 1999: *Jane's Underwater Warfare Systems*. 11th ed. Jane's Information Group, 259–276.

## **INITIAL DISTRIBUTION LIST**

1. Defense Technical Information Center  
Ft. Belvoir, Virginia
2. Dudley Knox Library  
Naval Postgraduate School  
Monterey, California