



DEVCOM DAC-TR-2022-005
January 2022

Modeling Space-Based Intelligence, Surveillance, and Reconnaissance (ISR) in Combat Simulations

by John Mazz

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so specified by other official documentation.

WARNING

Information and data contained in this document are based on the input available at the time of preparation.

TRADE NAMES

The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. The report may not be cited for purposes of advertisement.



DEVCOM DAC-TR-2022-005
January 2022

Modeling Space-Based Intelligence, Surveillance, and Reconnaissance (ISR) in Combat Simulations

by John Mazz

DEVCOM Analysis Center

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this 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 Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE January 2022		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) 1/2020–10/2021	
4. TITLE AND SUBTITLE Modeling Space-Based Intelligence, Surveillance, and Reconnaissance (ISR) in Combat Simulations			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) John Mazz			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Director DEVCOM Analysis Center 6896 Mauchly Street Aberdeen Proving Ground, MD			8. PERFORMING ORGANIZATION REPORT NUMBER DEVCOM DAC-TR-2022-005		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT To support future Multi-Domain Operations analyses, the DEVCOM Analysis Center (DAC) is exploring ways to represent the contribution of space-based Intelligence, Surveillance, and Reconnaissance assets in the Army's combat simulations. DAC is using the Framework for Capability-based Tactical Analysis Libraries and Simulations (FRACTALS) as a test-bed for methodology development. As a start, the Simplified General Perturbations 4 algorithm for predicting the orbital path of satellites has been incorporated into FRACTALS. This report focuses on imagery products available from commercial satellite constellations with resolutions of 1 m or less. Methods of predicting resolution as a function of sensor characteristics, slant range (including curvature of Earth), and viewing angle are presented. Examples of what can be perceived at various resolutions are also discussed.					
15. SUBJECT TERMS Space-based, ISR, NIIRS, Satellite, Cloud Cover, Resolution					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 29	19a. NAME OF RESPONSIBLE PERSON John Mazz
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) 410-278-6617

Table of Contents

List of Figures	iv
List of Tables	v
Acknowledgements	vi
1. INTRODUCTION	1
2. METHODOLOGY COMPONENTS.....	2
2.1 Satellite Positioning	2
2.2 Global Coverage and Collection Methods.....	2
2.3 Satellite Constellations.....	4
2.4 Resolution Examples	5
2.5 Satellite Earth Geometry.....	7
2.6 National Imagery Interpretability Rating Scale	9
2.7 Potential Methodology Approaches	13
2.8 Partial Cloud Cover.....	13
3. CONCLUSION.....	16
4. REFERENCES	17
Appendix A – List of Acronyms.....	A-1
Appendix B – Distribution List.....	B-2

List of Figures

Figure 1. Example of TLE data	2
Figure 2. Pléiades 1A and 1B combined corridor of visibility for the same day ($\pm 30^\circ$).....	3
Figure 3. Pléiades single-pass collection scenarios	4
Figure 4. Resolution/GSD example from Maxar	6
Figure 5. Maxar WordView-3 example intelligence product.....	7
Figure 6. Satellite earth geometry (from <i>Pléiades Imagery User's Guide</i>).....	8
Figure 7. NIIRS task example (civil NIIRS: cultural criteria).....	10
Figure 8. Cumulative distribution of possible NIIRS values when NIIRS 6.0 is predicted	12
Figure 9. Cloud-free and cloud-blocked LOSs on the first pass over the NAI.....	14
Figure 10. Cloud-free and cloud-blocked LOSs on a pass over the NAI 16 min after Figure 9	15

List of Tables

Table 1. Commercial Satellite Constellation Information as of 4 January 2022.....	5
Table 2. Nominal GSD Associate with NIIRS Level.....	10

Acknowledgements

The U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center recognizes the following individuals for their contributions to this report:

Brian Hairfield, DEVCOM Analysis Center

Eric Harclerode, DEVCOM Analysis Center

1. INTRODUCTION

During the 2021 Modeling and Simulation (M&S) Gap Forum, space intelligence, surveillance, and reconnaissance (ISR) modeling was identified as a current/near-future modeling gap. The U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center (DAC) submitted an Army M&S Enterprise Capability Gap white paper (Harclerode, 2021) describing a course of action to help fill this gap. The Army Modeling and Simulation Office has funded DAC to develop methodologies for representing performance of commercial, national, and military space and low-earth-orbit assets and their impact on joint operations with a test implementation within the Framework for Capability-based Tactical Analysis Libraries and Simulations (FRACTALS).

FRACTALS is a DAC-developed simulation framework that provides the generic architectural “building blocks” to model, simulate, and assess performance of ISR systems in tactical-level missions and tasks. FRACTALS serves as a test-bed for the various ISR performance methodologies developed at DAC to be incorporated into Force on Force simulations via methodology documentation and/or data. FRACTALS also serves as an analytical tool within DAC to execute performance analysis comparisons of ISR systems in tactical settings.

This effort will require some level of representation of satellite vehicles (altitude, trajectory, and kinematics), sensor payloads (electro-optical [EO], IR, synthetic aperture radar, and signals intelligence), networks, control systems, ground stations (timeline, communications, processing, exploitation, and dissemination), end users, and the processes and behaviors that connect them. This report describes some of the groundwork that DAC has performed to support this effort with a focus on visible-band camera imagery.

2. METHODOLOGY COMPONENTS

2.1 Satellite Positioning

FRACTALS represents the orbital location of satellites through use of the Simplified General Perturbations 4 (SGP4) algorithm and the Two-Line Element (TLE) Set. The TLE Set contains the orbital characteristics of a satellite at a single moment in time, and the SPG4 algorithm will extrapolate the satellite’s orbital location at a specific time in the future using the TLE set. Errors in orbital location will increase as the length of time between the TLE set and the extrapolation increases. Up-to-date TLE sets for commercial satellites can be obtained from websites such as www.n2yo.com. An example of a TLE set extracted from *Revisiting Spacetrack Report #3: Rev 2* (Vallado et al., 2006) is presented in Figure 1.

Card #	Satellite			Epoch			Mean motion derivative			Mean motion second derivative			Bstar (ER)			Elem num	Chk Sum							
	Number	Class	Designator	Yr	Day of Year (plus fraction)		(rev/day /2)			(rev/day ² /6)			S E											
	Year	Lch#	Piece				S			S			S		E									
1	16609	U	86017A	93	352	.53502934	.	00007889				00000-0					342							
			Inclination (deg)			Right Ascension of the Node (deg)			Eccentricity			Arg of Perigee (deg)			Mean Anomaly (deg)			Mean Motion (rev/day)			Epoch Rev			Chk
2	16609		51.6190	133.3340	00005770	102.5680	257.5950	15.59114070447869																

Figure 1. Example of TLE data

With the SGP4 algorithm and TLE sets, FRACTALS can predict the timing, duration, and resolution for satellite coverage of an area of interest on the ground.

2.2 Global Coverage and Collection Methods

Coverage and revisit rate (how much of the earth you can see and how often) are two defining features of satellite constellations. Figure 2, extracted from the *Pléiades Imagery User Guide* (ASTRIUM, 2012), shows the global coverage available from two satellites. Using both satellites with view angles within $\pm 30^\circ$, the revisit rate is 1.3 days or better above 40° latitude and 1.7 days at the equator. With view angles within $\pm 45^\circ$, daily revisits are possible. A nadir view has a view angle of 0° and is looking straight down.

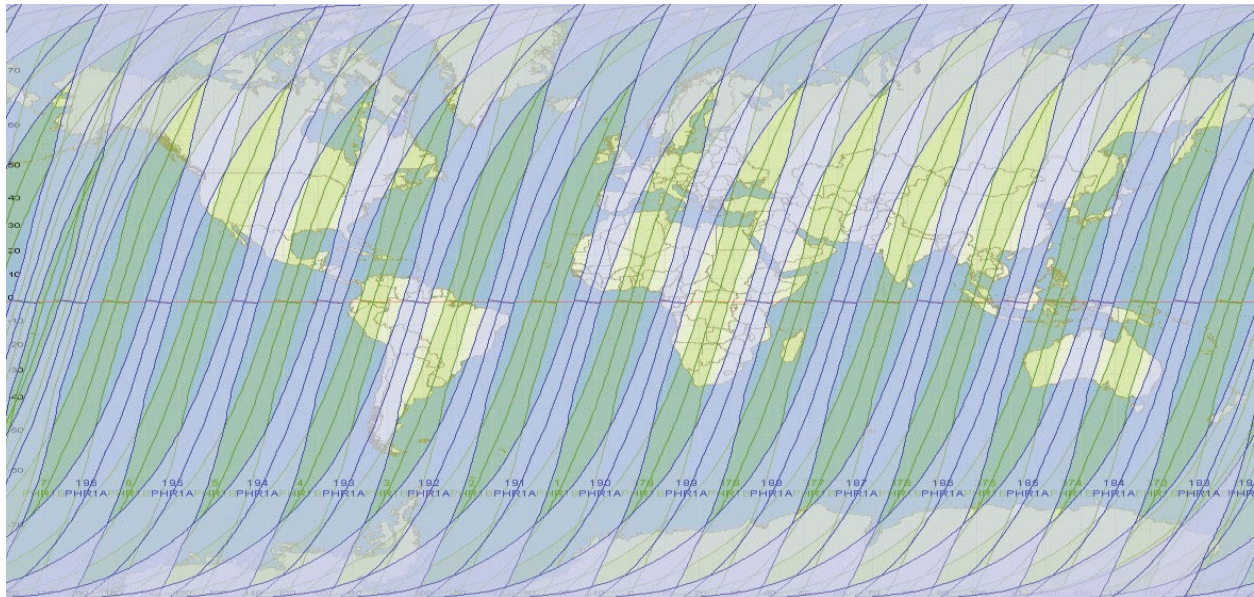


Figure 2. Pléiades 1A and 1B combined corridor of visibility for the same day ($\pm 30^\circ$)

There are various schemes for collecting satellite imagery. Figure 3 (also extracted from *Pléiades Imagery User Guide*) presents six single-pass collection scenarios available from the Pléiades satellite vendor.

1. Target Collection: typically 20 target locations within 1000- × 1000-km area
2. Multiple Acquisitions over a Crisis Area: typically 10 images over a 100- × 200-km area
3. Single Pass Strip Mapping: up to five contiguous strips of 150 km each
4. Stereo and Tri-Stereo: for 3D applications
5. Corridor Acquisition: follow linear features such as borders, coastlines, rivers, roads, railways, and pipelines
6. Multiple Acquisitions over a Single Target: up to 25 images over the same area for persistent surveillance mode to calculate speed and direction of moving targets

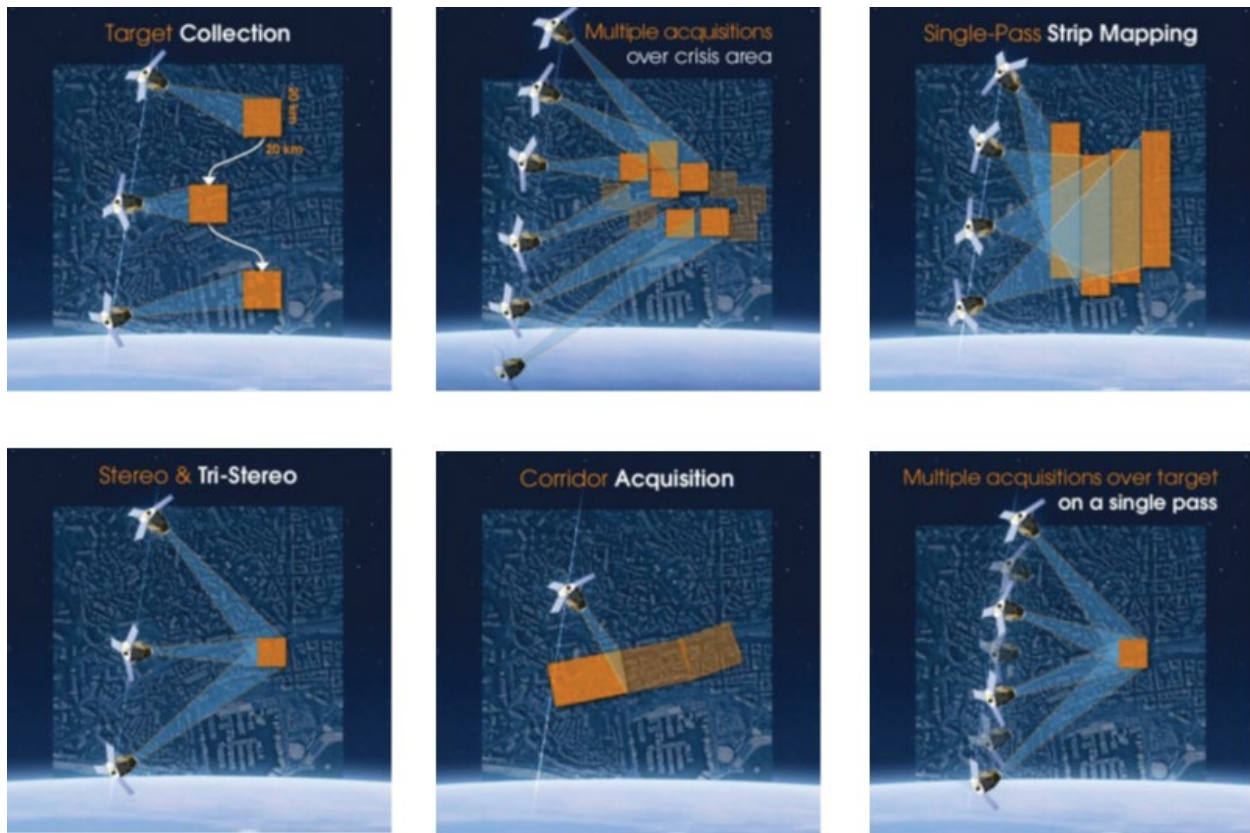


Figure 3. Pléiades single-pass collection scenarios

2.3 Satellite Constellations

There are many commercial satellite operators in the business of providing, processing, and analyzing imagery. Most vendors operate (or have access to) one or two satellites, while a few vendors operate large constellations of satellites. With larger constellations there can be multiple revisits to an area each day. Some vendors have goals to grow their constellations to achieve a revisit rate of every 15 to 20 min.

To be useful for ISR applications, satellite imagery should have a resolution of 1 m or less. This means that an image pixel projected on the ground should cover no more than 1 m on a side. This resolution is sometimes referred to as Ground Sampling Distance (GSD). Table 1 presents characteristics for the large commercial constellations with sufficient resolution to perform ISR missions, where CE90 is the circular error at the 90th percentile and NIIRS is the National Imagery Interpretability Rating Scale. Some of the constellations will expand in 2022, as noted in the number of satellites column in Table 1.

Table 1. Commercial Satellite Constellation Information as of 4 January 2022

Constellation Name	No. of Satellites	Altitude (km)	Nadir GSD (m)	NIIRS	Swath (km)	Geolocation Accuracy
BlackSky	13 + 4 (2022)	400–500	0.8–1.0	4.1–3.8	6.6	<10 m after processing
SkySat	21	400–600	0.72–1.1	4.6–4.0	5.9–8.0	30 m CE90
WorldView	3 + 6 (2022)	500–720	0.3–0.5	5.5–4.9	13.1–17.7	3.5–4.0 m CE90
NuSat	22 + ? (2022)	480–540	0.7–1.0	...	5	10 m CE90
Pléiades	2	700	0.7	4.4	20	8.5 m CE90
Pléiades Neo	2 + 4 (2022)	620	0.3		14	<5 m CE90
CartoSat-2	7	505–635	0.65–0.8	4.7–4.4	10	...
CartoSat-3	1 + 2 (2022)	509	0.25	...	16	...

The first three constellations in Table 1 are based in the United States, while NuSat is associated with Argentina, Pléiades with Europe/France, and CartoSat with India.

The GSD values represent nadir viewing and will increase as the look angle increases. The NIIRS values were estimated using the Night Vision – Integrated Performance Model (NV-IPM) when sufficient camera characteristics were known. Swath width and geolocation accuracy are self-reported by the vendor.

2.4 Resolution Examples

To illustrate what is achievable at various image resolutions, Maxar, the operator of the WorldView satellite constellation, provided the example presented in Figure 4 (EO Portal, 2022). At 1-m resolution you can detect two possible vehicles; at 70-cm resolution you can classify them as potentially armored vehicles; at 50-cm resolution you can recognize them as howitzers (based on size and shape), and at 30-cm resolution you can identify the type of howitzer.

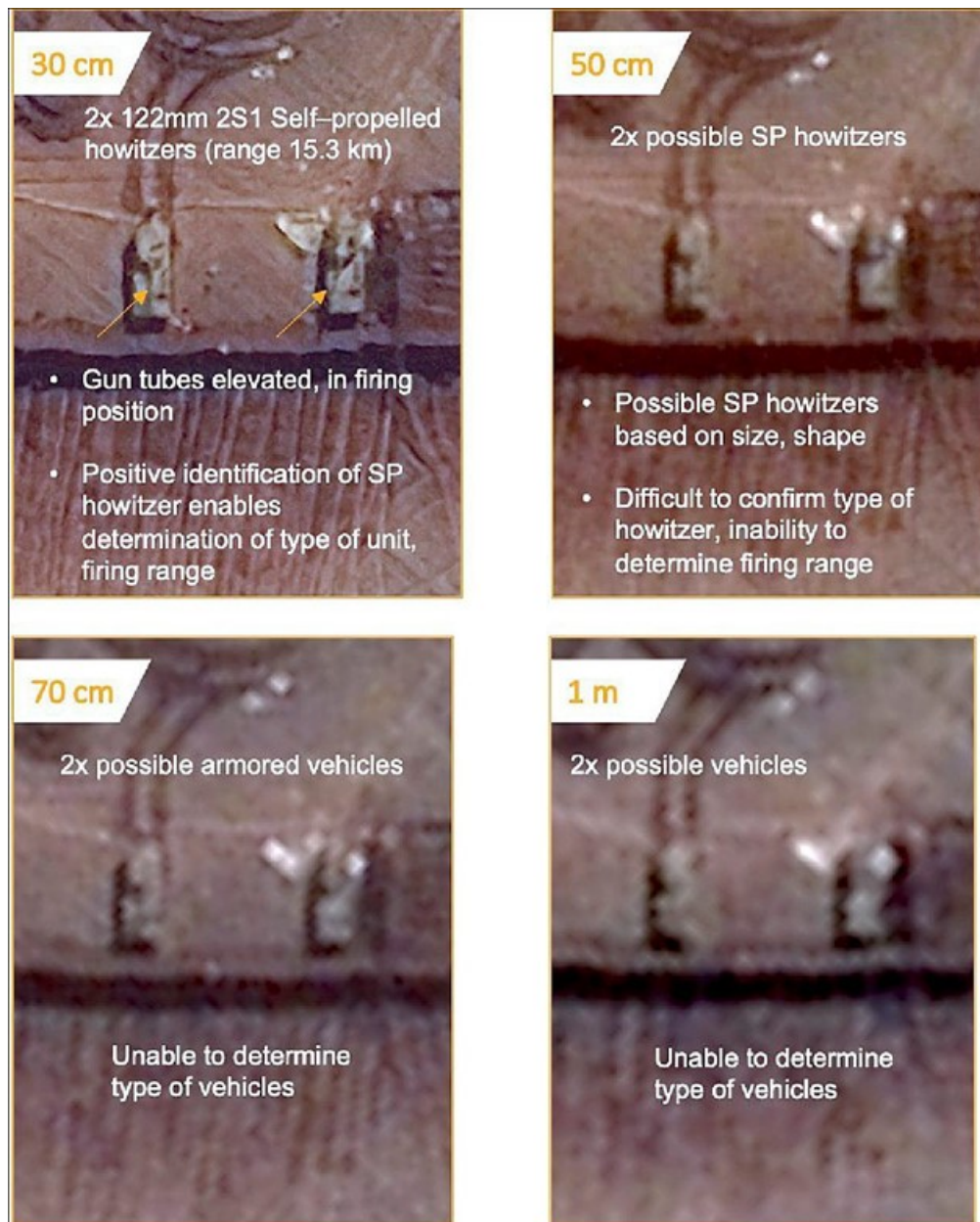


Figure 4. Resolution/GSD example from Maxar

In Figure 5 (EO Portal, 2022), Maxar presents a sample intelligence product available from WorldView-3 30-cm resolution imagery. Various military equipment is identified in this image collected over northern Syria.

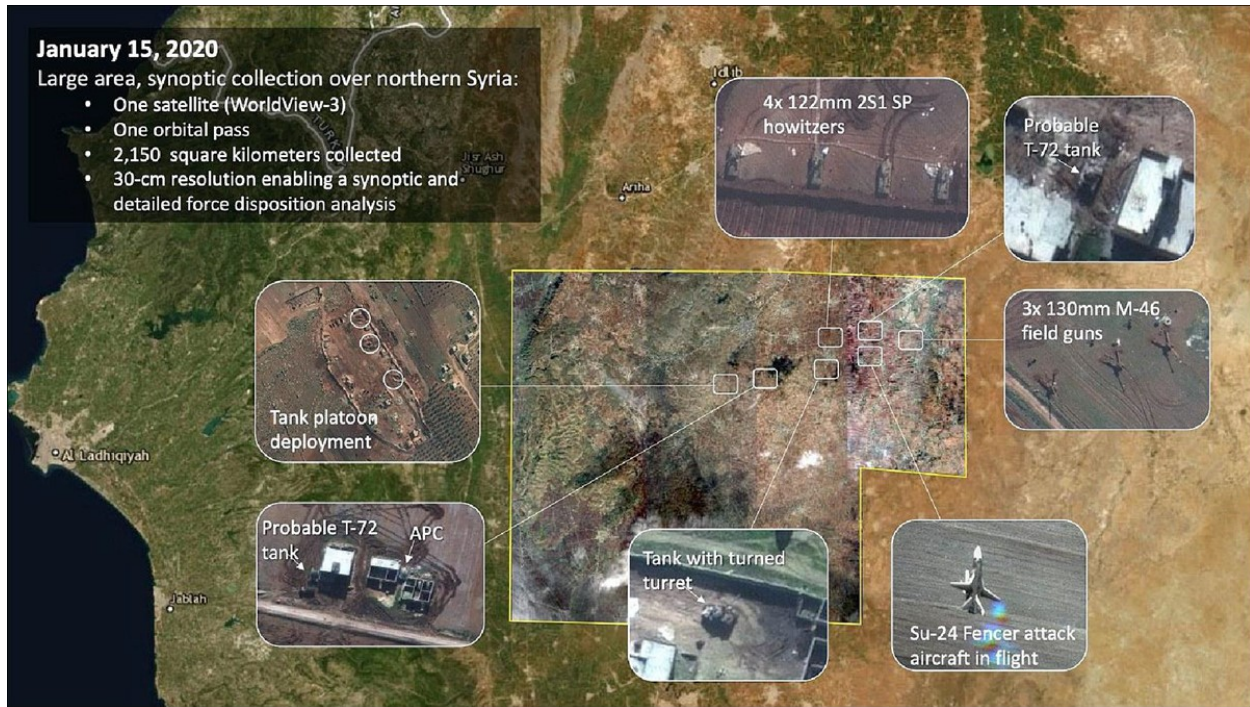


Figure 5. Maxar WorldView-3 example intelligence product

2.5 Satellite Earth Geometry

To get accurate estimates of slant range (SR) and GSD, the curvature of the earth must be considered. Figure 6 presents the Satellite Earth Observation Geometry, where h_{sat} is satellite altitude, R_E is radius of the earth (6367.45 km), and α is viewing angle off nadir (looking straight down). The equation for the incidence angle β is given in Figure 6. When calculating GSD, β must be used, not α .

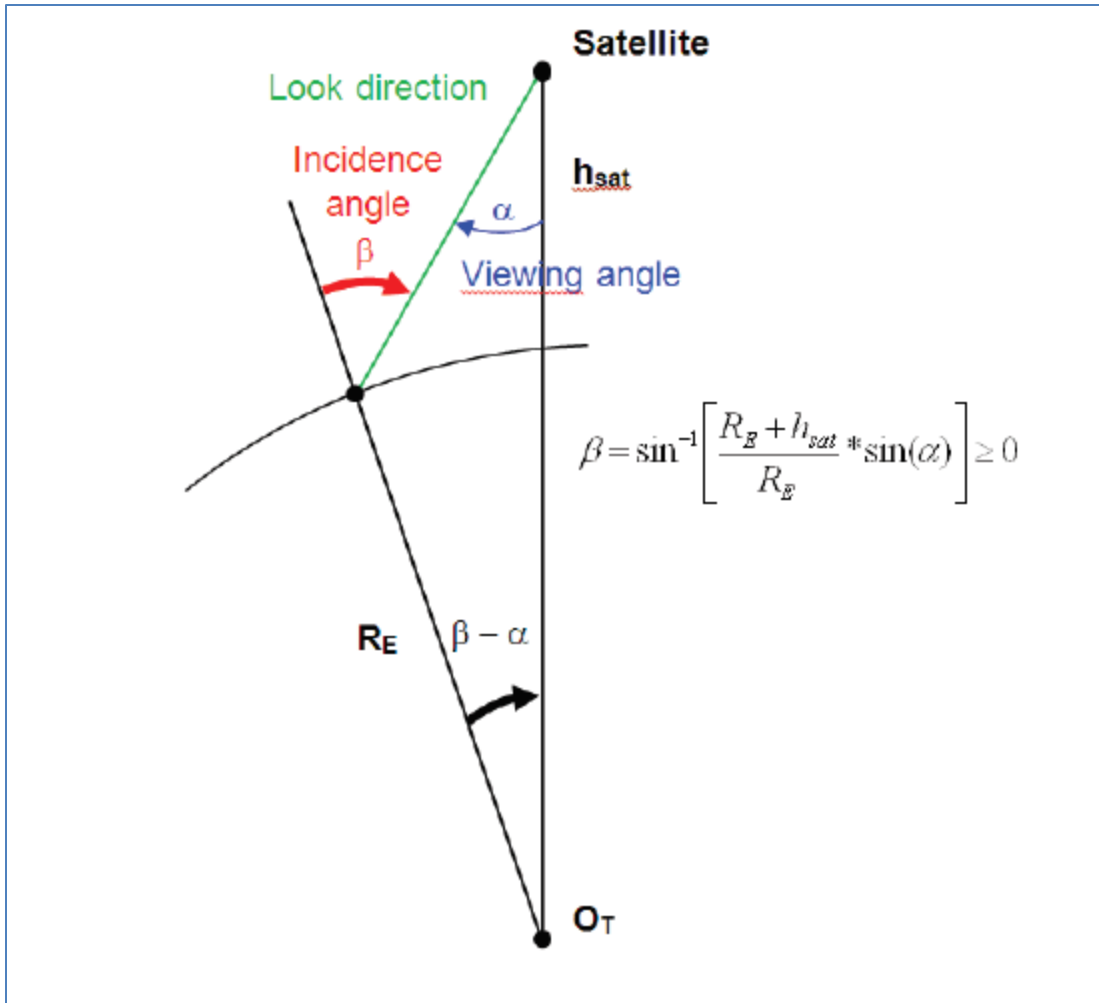


Figure 6. Satellite earth geometry (from *Pléiades Imagery User's Guide*)

SR is the green line in Figure 6 and can be determined by the Law of Cosines and the Quadratic Equation.

Law of Cosines

$$R_E^2 = SR^2 + (R_E + h_{sat})^2 - 2SR(R_E + h_{sat})\cos(\alpha)$$

$$SR^2 - 2(R_E + h_{sat})\cos(\alpha)SR + (R_E + h_{sat})^2 - R_E^2 = 0$$

Quadratic Equation

$$a = 1$$

$$b = -2(R_E + h_{sat})\cos(\alpha)$$

$$c = (R_E + h_{sat})^2 - R_E^2$$

Two solutions to the quadratic equation follow. The shorter one (SR) touches the earth, and the longer one (SR_{longer}) passes through the earth.

$$SR = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

$$SR_{longer} = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

When the term under the square root sign becomes negative, the slant path misses the earth entirely and the camera images atmosphere (earth limb) or space. The largest viewing angle for which the slant path still touches the earth (term under square root in the quadratic equation equals zero) is given by the following equation.

$$\alpha = \sin^{-1}\left(\frac{R_E}{R_E + h_{sat}}\right)$$

GSD is the distance that one image pixel subtends on the ground, and IFOV is the instantaneous field of view.

$$GSD_{vert}(m) = IFOV(rad) \frac{SR(km)}{\cos(\beta)} \times 1000$$

$$IFOV(rad) = \frac{pixel\ pitch(m)}{focal\ length(m)}$$

$$\beta = \sin^{-1}\left(\left(1 + \frac{h_{sat}}{R_E}\right) \sin(\alpha)\right)$$

$$GSD_{horz}(m) = IFOV(rad)SR(km) \times 1000$$

$$GSD = \sqrt{GSD_{horz}GSD_{vert}}$$

The GSD_{vert} calculated by NV-IPM uses α rather than β in the GSD_{vert} equation (flat earth assumption). This is not an issue for low altitudes, but could be an issue for calculating NIIRS for satellites. (*For Pléiades at a 695-km altitude, it is a difference of 4 cm in GSD_{vert} for $\alpha = 30^\circ$ and an underestimation of the SR by 15 km.*) It is possible to compensate for this with the Override Output feature in NV-IPM.

2.6 National Imagery Interpretability Rating Scale

NIIRS directly relates image quality to interpretation tasks that can be performed. NIIRS is a 10-point scale, with 0 providing no useful information and 9 providing great detail. GSD is a major component affecting the NIIRS ratings; however, sensor blur and noise characteristics also play a role. Table 2 presents an approximate relationship between

NIIRS and GSD. Figure 7 presents an excerpt from the Civil NIIRS Cultural Criteria task table for NIIRS levels 5, 6, and 7 ([IRARS], 1996), equating to GSDs ranging from 0.20 to 1.2.

Table 2. Nominal GSD Associate with NIIRS Level

NIIRS Rating	GSD (meters)
0	NA
1	>9.0
2	4.5–9.0
3	2.5–4.5
4	1.2–2.5
5	0.75–1.2
6	0.40–0.75
7	0.20–0.40
8	0.10–0.20
9	<0.10

LEVEL 5

Identify raw materials (e.g., lumber, sand, gravel, bricks) in a residential construction area. (NIIRS 5.0)

Identify individual lines painted on paved roads, aprons, parking lots. (NIIRS 5.1)

Distinguish between wheeled and tracked vehicle tracks. (NIIRS 5.1)

Identify large construction equipment by type (e.g., bulldozer, backhoe, road grader). (NIIRS 5.2)

Identify individual telephone/electric poles in residential neighborhoods. (NIIRS 5.4)

Identify fallen utility poles. (NIIRS 5.5)

Detect lines on track, basketball, volleyball, tennis, baseball, soccer playing areas. (NIIRS 5.5)

Identify individual 55 gallon drums in an open storage facility. (NIIRS 5.7)

LEVEL 6

Detect individuals, when not in a group. (NIIRS 6.2)

Identify pole-mounted electrical transformers in residential neighborhoods. (NIIRS 6.4)

Detect small road signs (e.g., stop, yield, speed limit) in an urban area. (NIIRS 6.6)

Identify building materials of urban structures (e.g., brick, wood, concrete, stucco, tile, adobe). (NIIRS 6.8)

Identify flags on a green at a golf course. (NIIRS 6.9)

LEVEL 7

Identify individual above ground utility lines in a residential neighborhood. (NIIRS 7.1)

Identify a manhole cover. (NIIRS 7.1)

Identify a fire hydrant. (NIIRS 7.2)

Identify limbs (arms, legs) on an individual. (NIIRS 7.3)

Figure 7. NIIRS task example (civil NIIRS: cultural criteria)

NIIRS values are assigned to imaging systems, imagery, and imagery products by a panel of trained image analysts; however, this can be an expensive and time-consuming process. The General Image Quality Equation (GIQE) was developed as a means to estimate NIIRS values for an imaging system.

The GIQE is modeled in NV-IPM as follows:

$$NIIRS = C - a \log_{10}(GSD * 100/2.54) + b \log_{10}(RER) - 0.656H - 0.344G/SNR$$

$$C = 10.751 \text{ (thermal sensor) or } 10.251 \text{ (visible sensor)}$$

GSD = Ground Sampling Distance in meters

RER = Relative Edge Response

H = Edge Overshoot

G = Additional Noise Gain

SNR = Signal to Noise Ratio

If RER ≥ 0.9, a = 3.32 and b = 1.559

If RER < 0.9, a = 3.16 and b = 2.817

NV-IPM can be used to calculate NIIRS, GSD, RER, H, G, and SNR. For the most part, RER, H, and G do not vary much with range, C_n^2 , or altitude, and can be modeled as constants in FRACTALS. However, GSD and SNR will need to be modeled explicitly. GSD can be modeled as previously described in Section 2.5, Satellite Earth Geometry.

For NIIRS of thermal imagery in NV-IPM, SNR is a function of ΔT (difference in temperature between the target and background) and atmospheric transmission. For simplicity, FRACTALS can be provided with the SNR_0 generated by NV-IPM when $\Delta T = 1$ and atmospheric transmission is set to 1.0/km. SNR as a function of SR can be generated as follows:

$$SNR(R) = SNR_0 * \Delta T * Transmission(R)$$

For NIIRS of visible imagery in NV-IPM, SNR is a function of light level (LL), contrast, atmospheric transmission, and sky over ground (SOG) ratio. For simplicity, FRACTALS can be provided with the SNR_0 for each light level generated by NV-IPM when target contrast ($TgtCon$) is 0.25, atmospheric transmission is set to 1.0/km, and SOG = 1 and SNR as a function of SR and LL can be generated as follows:

$$SNR(R, LL) = SNR_0(LL) * \frac{|TgtCon|}{0.25} * \frac{1}{1 + SOG \left(\frac{1}{Transmission(R)} - 1 \right)}$$

The following is a short description of work in progress to explore the possibility of assessing a probability of accomplishing an NIIRS task (PANT).

- There are uncertainties in the GIQE prediction. The standard errors (SEs) in the fit of the GIQE to the validation data sets are 0.3 for visual imagery and 0.38 for thermal imagery. Could the SE be used to assign a PANT? Figure 8 shows the cumulative distribution of possible NIIRS values when an NIIRS value of 6.0 is predicted by the GIQE (SE = 0.3). From Figure 8 it can be seen that the 95% confidence interval for the prediction is 6.0 ± 0.5 or (5.5, 6.5). Of course, this would imply that there is only a 0.5 probability of performing an NIIRS 6.0 task, a 0.65 probability (1.0–0.35) of performing an NIIRS 5.9 task, and a 0.95 probability (1.0–0.05) of performing an NIIRS 5.5 task when the GIQE predicts an NIIRS of 6.0.
- Since it is unlikely that all image analysts will agree, there could also be some uncertainty in the NIIRS level assigned to a specific task. In Figure 7, an NIIRS of 5.5 was assigned to the task of identifying fallen utility poles. Was that derived from five image analysts assigning an NIIRS of 5.0 and five image analysts assigning an NIIRS of 6.0? This would give an average of 5.5 and a standard error of 0.167. DAC currently lacks a source for the SE associated with the historical NIIRS level task assignments.
- Ideally, PANT estimates should take into account both sources of uncertainty (GIQE prediction error and NIIRS-level task assignment variability); thus, this PANT effort remains a work in progress.

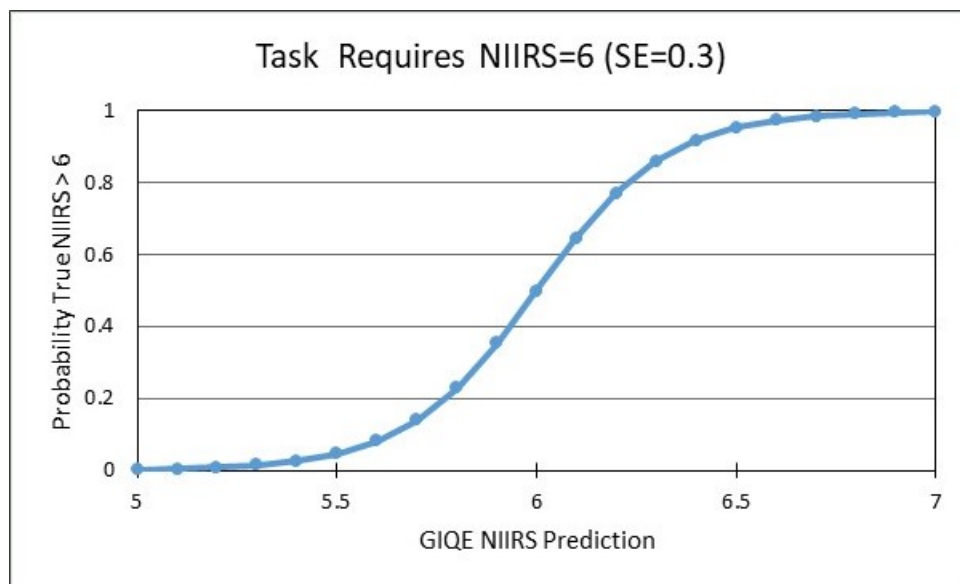


Figure 8. Cumulative distribution of possible NIIRS values when NIIRS 6.0 is predicted

2.7 Potential Methodology Approaches

Per Satellite Approach:

1. Determine the NIIRS and GSD required to perform the desired space-based ISR task. If the task does not have a predefined NIIRS value, surrogate the NIIRS value from a task perceived to be of similar difficulty. Due to the subjective nature of surrogation, it is best performed by a group rather than an individual. A simpler approach would be to select a GSD at which all desired spaced-based ISR tasks can be performed and skip the NIIRS approach.
2. Determine the off-nadir viewing angle required to view a named area of interest (NAI) on the satellite's current pass.
3. Calculate the NIIRS and GSD for the off-nadir viewing angle. Is NIIRS greater than or GSD less than what is required? If so, the desired space-based ISR tasks can be performed.

Window of Opportunity Approach:

1. The satellite or constellation of satellites can only perform the task when the off-nadir viewing angle required to view the NAI is within $\pm X^\circ$ (based on NIIRS or GSD required to perform the desired space-based ISR task).
2. Using the predicted orbital paths for the constellation of satellites, what are the windows of opportunities to view the NAI?
3. Execute missions in FRACTALS during these windows of opportunity. A second satellite pass may be required to perform the battle damage assessment.
4. Cloud cover may negate a window of opportunity.

2.8 Partial Cloud Cover

Visible- and thermal-band satellite cameras cannot penetrate overcast cloud cover conditions; however, these cameras can see through gaps in the cloud cover.

In the 1970s and 1980s, research was conducted in predicting the probability of cloud-free line of sight (PCFLOS), the recurrence of CFLOS and the persistence of CFLOS. PCFLOS is a function of the percent cloud cover reported and the view angle of the LOS path; however, PCFLOS is relatively insensitive to the range of view angles relevant to satellite imagery. Empirically, 50% cloud cover yields a PCFLOS of about 0.75, indicating that human observers tend to overestimate the reported cloud cover.

If a satellite has CFLOS to an NAI at time t_0 and the next satellite has CFLOS to the NAI 20 min later at time t_{20} , LOS is said to have recurred. If CFLOS exists during the entire time between t_0 and t_{20} , LOS is said to have persisted over the 20 min. For the

commercial satellite constellations, LOS recurrence is the relevant metric. Mathematically, this could be represented by a bivariate Bernoulli distribution relating the occurrence of CFLOS at a specific location at two different points in time.

The cloud maps in Figures 9 and 10 give an example of how recurrence could be modeled.

1. Place a grid over the NAI and let each grid cell represent 1×1 km for a total NAI of 10×10 km.
2. Assume 50% cloud cover, which yields PCFLOS = 0.75.
3. Randomly assess each cell against the 0.75. If the random number is <0.75 , place a zero in the cell, representing CFLOS; otherwise, place a 1 in the cell representing cloud-blocked LOS.
4. Calculate the transition matrix from the bivariate Bernoulli. If we assume a 16-min time interval, the Bernoulli correlation is 0.6 for 50% cloud cover. The probability that a cell that is cloud-free will again be cloud-free is 0.9, and the probability that a cell that is cloud-blocked is again cloud-blocked is 0.7.
5. Randomly assessing each cell in Figure 9 by the appropriate transition probability yields the cells in Figure 10.

1	0	0	0	0	0	1	0	0	1
0	0	1	0	1	1	0	0	1	0
0	1	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0
1	0	0	0	0	0	1	0	0	0
0	1	0	0	1	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0
0	0	0	1	0	0	1	0	1	0
1	1	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	1	1	1

Figure 9. Cloud-free and cloud-blocked LOSs on the first pass over the NAI

1	1	0	0	0	0	1	0	0	0
0	1	1	0	0	0	0	0	1	0
0	1	0	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	0	0
1	0	0	0	0	0	0	0	0	0
0	1	0	0	1	0	0	0	0	0
0	0	0	1	0	0	1	0	0	0
0	0	0	1	0	0	1	0	1	0
1	0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	1	1	0	0

Figure 10. Cloud-free and cloud-blocked LOSs on a pass over the NAI 16 min after Figure 9

Some cells are cloud-blocked on both satellite passes, but could have CFLOS on a subsequent satellite pass.

3. CONCLUSION

The Army Modeling and Simulation Office has funded a DAC effort to develop methodologies for representing the performance of commercial, national, and military space and low-earth-orbit assets and their impact on joint operations with a test implementation within the FRACTALS simulation framework.

Visible-band camera imagery providing 1-m or better resolution was the focus of the methodology components discussed. Current commercial satellite constellations that meet this resolution requirement were identified. FRACTALS has implemented the SGP4 algorithm to represent the orbital paths of the satellites. Methods for calculating NIIRS and GSD were presented. A method for representing the effect of partial cloud cover was also addressed.

4. REFERENCES

ASTRIUM (an EADS Company). (2012, October). *Pléiades Imagery User Guide, v2.0*.

EO Portal Directory. (2022). *WorldView legion constellation*.

[https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-
legion](https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-
legion)

Harclerode, Eric. (2021, June 9). *Sensors: space ISR modeling and simulation gap ID no. S.4 Army M&S enterprise capability gap white paper*. U.S. Army Combat Capabilities Development Command Analysis Center.

[IRARS] Imagery Resolution Assessments and Reporting Standards (IRARS) Committee. (1996, March). *Civil NIIRS reference guide appendix II: additional NIIRS criteria*. https://fas.org/irp/imint/niirs_c/app2.htm

Vallado, David, Crawford, Paul, Hujsak, Richard, & Kelso, T.S. (2006). *Revisiting Spacetrack Report #3: Rev2*. American Institute of Aeronautics and Astronautics Report No.: AIAA 2006-6753-Rev2.

Appendix A – List of Acronyms

3D	three-dimensional
CE90	circular error 90%
CFLOS	cloud-free line of sight
DAC	DEVCOM Analysis Center
DEVCOM	U.S. Army Combat Capabilities Development Command
EO	electro-optical
FRACTALS	Framework for Capability-based Tactical Analysis Libraries and Simulations
G	additional noise gain
GIQE	General Image Quality Equation
GSD	Ground Sampling Distance
H	edge overshoot
IFOV	Instantaneous Field of View
IR	infrared
ISR	intelligence, surveillance, reconnaissance
LL	light level
LOS	line of sight
M&S	Modeling and Simulation
NAI	named area of interest
NIIRS	National Imagery Interpretability Rating Scale
NV-IPM	Night Vision – Integrated Performance Model
PANT	probability of accomplishing an NIIRS task
PCFLOS	probability of cloud-free line of sight
R_E	radius of earth
RER	relative edge response
SE	standard error
SGP4	Simplified General Perturbations 4
SNR	signal to noise ratio
SOG	sky over ground
SP	self-propelled
SR	slant range
TLE	Two-Line Element

Appendix B – Distribution List

ORGANIZATION

DEVCOM Army Research Laboratory
FCDD-RLD-DCI/Tech Library
2800 Powder Mill Rd.
Adelphi, MD 20783

Defense Technical Information Center
ATTN: DTIC-O
8725 John J. Kingman Rd.
Fort Belvoir, VA 22060-6218

DEVCOM Analysis Center
FCDD-DAE-I/John P. Mazz
6896 Mauchly St.
Aberdeen Proving Ground, MD 21005-5071

U.S. Army Center for Army Analysis
ATTN: CPT Lorraine G. Dunwoody
6001 Goethals Road
Fort Belvoir, VA 22060-5230