CHAPTER 9

INTERACTIVE COMPUTER GRAPHICS: THE ARMS RACE

D. W. HAFEMEISTER
PHYSICS DEPARTMENT
CALIFORNIA POLYTECHNIC UNIVERSITY
SAN LUIS OBISPO, CA 93407

ABSTRACT

By using interactive computer graphics (ICG) it is possible to discuss the numerical aspects of some arms race issues with more specificity and in a visual way. The number of variables involved in these issues can be quite large; computers operated in the interactive, graphical mode, can allow exploration of the variables, leading to a greater understanding of the issues. This paper will examine some examples of interactive computer graphics: (1) the relationship between silo hardening and the accuracy, yield, and reliability of ICBMs; (2) target vulnerability (Minuteman, Dense Pack); (3) counterforce vs. countervalue weapons; (4) civil defense; (5) gravitational bias error; (6) MIRV; (7) national vulnerability to a preemptive first strike; (8) radioactive fallout; (9) digital image processing with charge-coupled devices.

I. INTRODUCTION

I.A. Methodologies: Words, Equations, Pictures, and ICG. In spite of the fact that so much has already been written about the arms race, some general confusion about the strategic importance of various missile systems and strategies continues. This paper explores the possibility of using the visual medium through interactive computer graphics (ICG) to learn about the arms race. ICG has three distinct advantages: (1) interactive, visual education; (2) debating policy; and (3) "networking" information.

We often have been told that "a picture is worth a thousand words;" the interactive pictures of ICG may be an improved medium for increasing our understanding of the arms race. The computer can relate both to our logical, mathematical left side of the brain as well as to the more intuitive right side of the brain as has been indicated by Sperry[1] and others. Gradel and McGill[2] have pointed out that "The graphical presentation of the results of complex computer model calculations is frequently as important as the computation, since it is generally through such presentations that the modeler and the modeler's audience derive the maximum amount of information." Since the deluge of words in our society has weakened the strength of verbal communication,

0094-243X/83/1040184-21 $3.00

numbers have often taken on a greater political power than they deserve, both because they appear to be more reliable, and because they are not understood. ICG can correct this tendency by allowing both sides to explore and understand the variation in the data sets that are used to prove the "bottom line." Thus, ICG can be used both for educating and for debating national security policy. Of course, there is a limit to what can be quantified in these debates since the uncertainties of the arms race are larger than the certainties; nevertheless, we should try to be as accessible and accurate as possible when we do quantify. Lastly, ICG diskettes can be copied and mailed easily to those who wish to study and teach numerical aspects of the arms race; this ability to "network" information adds a new dimension to printed words and equations.

In this paper we will consider some simplified models of "war games" that can be used in interactive computer graphics. Most of these results can be obtained as easily with mathematical equations alone; but our purpose is to enhance the transfer of knowledge to those who are uncomfortable with the use of equations. In our ICG program "First Strike" (Sec. VI) we will use ninety adjustable parameters; only with ICG can one keep track of this plethora of parameters which seem to become further removed from reality the more we "talk" about them. Ultimately one can not use equations and parameters alone to describe the "action-reaction" escalation of the arms race and the degree of stability from mutually assured destruction (MAD), but these mathematical models do set some limits on what actually could be done, and they do give some meaningful insights into the interactions that effect the outcomes of these difficult issues.

I.B. Graphics. Computer graphics involves a number of tricks of the trade: the ability to "page-flip" between the two pages of high-resolution graphics; the use of toggle switches to input data to the computer; the ability to rapidly scale and rotate shape tables for animation; the use of "Easy Draw" to prepare large figures such as maps; the scaling and transformation of images; the use of light pens, joy sticks, graphics tablets, and graphics printers; and other processes. An excellent text on these graphics techniques has been been written by R. Myers[3]; those who would like to learn more about these topics can purchase a diskette with about 70 graphics programs that accompany the text. It is interesting to point out that undergraduate students are often more creative and faster with developing sophisticated graphics than many faculty; perhaps, this is because learning to use such terminology as peek and poke are very much like learning a new foreign language. At any rate, perserverance can overcome most graphics

problems. Some of these graphics tricks are highlighted in the manual on ICG which is available to accompany our diskette (Sec. XI).

To demonstrate the power of interactive computer graphics, we will examine the following issues in the sections listed below: (II-IV) Target Vulnerability: The tradeoff between accuracy, yield, hardness, reliability, and gravitational bias error; Minuteman vulnerability; first and second strike weapons; Dense Pack MX; and civil defense. (V) Multiple Independently Targetable Reentry Vehicles (MIRV). (VI) National vulnerability to a preemptive first strike; is it possible? (VII) Distribution of radioactive fallout after a nuclear attack. (VIII) Digital image processing to enhance verification; the use of charge-coupled device cameras that can be used directly with computers.

II. TARGET VULNERABILITY

We shall begin by considering in detail an example that can be discussed with equations or ICG; the example is the case of an attack on the U.S. Minuteman force by Soviet SS-18 missiles. Sec. II will consider some equations, Sec. III will consider ICG, and Sec. IV will broaden the discussion to include the effects of a possible gravitational bias error.

II.A. Parameters. If the accuracy of a missile is increased, it follows that the yield necessary to carry out a mission against a hardened military target can be correspondingly reduced. As accuracy increased by a factor of twenty from about 5 miles in 1954 to 1/4 mile in 1970, the U.S. decreased the yield of its warheads by a factor of about 100 from 9 megatons (Mt) for the Titan ICBM to 50 kilotons (kt) for Polaris/Poseidon and 170 kt for Minuteman. Increased accuracy was the necessary precursor to the deployment of smaller warheads used with Multiple Independently Targetable Reentry Vehicles (MIRV) for counterforce purposes. The new technologies available to the cruise missile have further increased accuracy to less than 10 m. The tradeoff between accuracy and yield (for hardened targets) can be qualitatively understood by considering the empirical relationship[4] for blast over-pressure derived from nuclear testing (surface blasts):

$$p = (14.7)(Y/r^3) + (12.8)(Y/r^3)^{1/2} \qquad (1)$$

where p is the overpressure in psi, Y is the yield in Mt, and r is the distance in nautical miles (1 nm = 1852 m). For the case of "silo-busting" attack on Minuteman where high pressures are needed, one need consider only the first term in Eq. 1. Since accuracy improved by a

factor of 20 from 1954 to 1970, it follows that the yield could have been reduced by a factor of $(20)^3 = 8000$ in order to carry out the same military mission. Since the yield was reduced by a factor of only 100, the additional effective yield of Minuteman and Polaris/Poseidon can be used to overcome hardened missile sites and to increase the probability of a successful mission. The miniaturization of nuclear weapons has also enhanced the relative ability to destroy surface area (as well as point targets) since the total destructive area is increased (per Mt) with a larger number of smaller weapons.

II.B Minuteman Vulnerability. In order to give some feeling for the numbers involved in Minuteman vulnerability, let us calculate[5] the single shot kill probability (SSKP = P_k) for a missile attacking a hardened silo:

$$P_k = 1 - e^{-(Y^{2/3}/B\ CEP^2\ H^{2/3})} \qquad (2)$$

where $B = 0.22$ when Y is in Mt, H is the silo hardness in psi, and CEP (circular error probable) is the accuracy in nm. We can determine the SSKP of destroying a Minuteman silo assuming the following parameters[5-8]: (1) Minuteman silos are hardened to about $H = 2000$ psi; (2) The Russian SS-18 warheads typically have a yield $Y = 0.75$ Mt and a CEP = 280 m (0.15 nm, at some point in the future); and (3) The reliability of an SS-18 is, perhaps, $R = 0.8$. Using these parameters, the SSKP for the SS-18 on a Minuteman silo is $P_k = 1 - e^{-1.05} = 1 - 0.35 = 0.65$. The SSKP should be multiplied by the reliability of the SS-18 to obtain the success rate for each SS-18 warhead; we obtain 52% for $R = 0.8$, and 59% for $R = 0.9$. For the case of aiming two SS-18 reentry vehicles from different launchers at a given silo, the kill probability is $P_{k2} = 1 - (0.48)^2 = 77\%$ for $R = 0.8$ and 83% for $R = 0.9$. Because one incoming warhead can destroy another incoming warhead (the fratricide effect), the two incoming warheads must arrive less than about 10 seconds from each other. For this reason we do not have to consider the case of three or more incoming warheads; nevertheless, for the case of 3 independent SS-18's, the success rate would be $P_{k3} = 1 - (0.48)^3 = 89\%$ for $R = 0.8$. Since there are 1000 Minuteman missiles, these results imply that, perhaps, 170 to 230 would survive two SS-18's, and 100 would survive 3 SS-18's. The latter case would consume the entire SS-18 force since there are about 308 SS-18 launchers and each could be MIRVed about 10 times. From this analysis we can conclude that "Minuteman vulnerability" means that the U.S. would have between 100 to 250 Minuteman launchers (200 to 600 warheads) remaining after a Russian first-strike attack. These calculations consider neither the possibility of

systematic bias errors (Sec. IV) nor the other armaments that are available to deter such an attack (Sec. VI).

II.C Dense Pack. It has been proposed to base the MX missile in a very closely packed matrix (545 m apart) so that incoming missiles would destroy each other (fratricide). Let us determine the minimum value of the hardness (H in psi) of the MX silos that would prevent incoming warheads of yield Y = 0.75, 1, 5, and 25 Mt from destroying more than one MX silo. Since the nearest neighbor spacing is 545 m, an incoming warhead that landed halfway between two silos would be 273 m from each silo. Using the formula for overpressure from surface blasts (Eq. 1), we obtain the following values: H > 3500 psi for 0.75 Mt warheads; H > 5000 psi (1 Mt); and H > 22,000 psi (5 Mt), and H > 110,000 psi (25 Mt). In addition, one must consider the size of the craters from these warheads; if the radius of the crater[4,9] is greater than 275 m, both silos could be destroyed. By using the Rand Corporation "Bomb Damage Effect Computer" (1964), we have obtained the radii of the craters in rock: r = 142 m (0.75 Mt), r = 158 m (1 Mt), r = 279 m (5 Mt), and r = 485 m (25 Mt). These crater radii (in rock) can be approximately described by $r \cong 160\ Y^{0.3}$ where r is in meters and Y is in Mt. By building silos in more resilient rock media it is possible to reduce the effect of these craters somewhat, but it is clear that a very large warhead would create a large enough crater to destroy two MX silos. (There is some recent evidence that these crater radii for very large weapons must be reduced by about a factor of two.)

III. TARGET VULNERABILITY WITH ICG

III.A ICG. The complexity of the equations of Sec. II is usually enough to dissuade most people from moving from a discussion of the trees (equations) to a broader discussion of the forest (stability in the arms race as affected by numbers). To obtain a view of the forest we will use ICG to obtain a "physical feel" for the parameters and equations dealing with target vulnerability. We will briefly describe the ICG program "Bombs" which has five adjustable parameters: yield (Y), accuracy (CEP), hardness (H), number of warheads aimed at a silo (L), and gravitational bias error (Sec. IV). The program "Bombs" assumes 100% reliability for the incoming warheads; it could be modified with a random number generator to account for less than 100% reliability. Bombs does the following: it calculates the kill radius (r_k) of a warhead as a function of the yield of the warhead and the hardness of the silo; it scatters circles with a radius of r_k about the aim point with an accuracy of CEP using Gaussian statistics; it simulates

gravitational bias error by shifting the aim point with a joy stick; the key "Q" can be used to call up the menu to scale the graphics and to vary Y, CEP, and H.

The program calculates the kill radius (in nm) of a surface blast as a function[5] of the yield of the weapon and the hardness (H = p in Eq. 1) of the target;

$$r_k = \{Y/(0.068H - 0.23H^{1/2} + 0.19)\}^{1/3} . \qquad (3)$$

For example, the kill radius of an SS-18 warhead (0.75 Mt) will vary depending on the hardness of the intended target: For a Minuteman silo (2000 psi), r_k = 335 m (0.18 nm); for superhardening Minuteman to H = 5000 psi for MX deployment, r_k = 245 m (0.13 nm); for a horizontal MX (600 psi), r_k = 510 m (0.28 nm); for cities with H = 5 psi, r_k = 6.7 km (3.6 nm); and for civil defense with H = 30 psi, r_k = 1.7 km (0.92 nm). Similarly, the kill radius will vary depending on the yield of the warhead that is aimed at a Minuteman silo (H = 2000 psi): for Y = 0.75 Mt, r_k = 335 m (0.18 nm), for Y = 0.35 Mt (MX), r_k = 260 m (0.14 nm); and for Y = 0.1 Mt (Trident), r_k = 170 m (0.093 nm). In Figure 1, the computer graphics has drawn the circles associated with these kill radii.

The accuracy of the incoming missiles is incorporated into the program in the following way: The program assumes that the individual missiles are randomly spread about the aim point with a normal Gaussian distribution;

$$P(r) = (1/2\pi\sigma^2) e^{-r^2/2\sigma^2} , \qquad (4)$$

with σ = CEP/1.17. This implies no systematic bias error; the distribution is centered about the aim point at r = 0. The program does its calculation on a rewritten form of Eq. 4 to obtain the random radius for this Gaussian distribution,

$$r(\text{random}) = - (2^{1/2}\sigma) \ln(\text{Rnd}) \qquad (5)$$

where Rnd is a random number between 0 and 1 generated by the computer. In addition, the program assumes random angles for the missiles with respect to the aim point. With these assumptions, "Bombs" can graph the case of SS-18 (Y = 0.75 Mt) aimed at Minuteman silos (H = 2000 psi) with an accuracy of CEP = 0.15 nm = 280 m (in 1985?). For the case of 100 independent SS-18 warheads falling on Minuteman, "Bombs" calculates (see Fig. 2) that 30 missiles survive and that 70 missiles are destroyed. This is statistically consistent with Eq. 2 which indicates that 35% of the Minuteman force would survive an attack of one SS-18 of 100% reliability on one silo. In 1981 and 1983 the U.S. government has proposed placing the MX missile in superhardened Minuteman silos

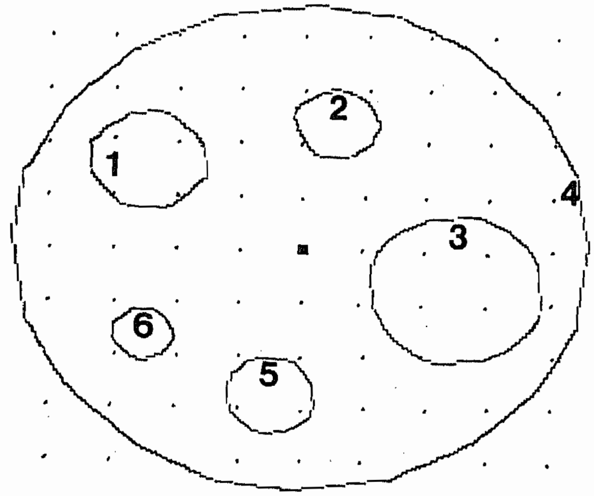

Fig. 1. KILL RADII: The kill radius of a missile is a function of the yield (Y) of the missile and the hardness (H) of the silo (Eq. 3). The dots in the figure are 0.2 nautical miles (1 nm = 1852 m) apart, and the matrix of dots is 1.6 nm (1.85 miles) on a side. For the case of the SS-18 missile (Y = 0.75 Mton) the ICG program "Bombs" has drawn the following circles: (1) H = 2000 psi for the Minuteman silo, (2) H = 5000 psi for the superhardened Minuteman silo, (3) H = 600 psi for the horizontal MX missile, and (4) H = 30 psi for the urban area with civil defense. For normal urban areas of H = 5 psi, the kill radius is offscale since it is 3.6 nm (6.7 km = 4.2 miles). For the case of the Minuteman silos with H = 2000, circles have been drawn for (1) Y = 0.75 Mton (SS-18), (5) Y = 0.35 Mton for the MX missile, and (6) Y = 0.1 Mton for the Trident submarine. The circles appear elliptical in shape because of the Apple graphics.

Fig. 2. HARDENED MINUTEMAN SILOS: The pattern of missiles is distributed about the aim point according to Gaussian statistics (Eq. 4). In the upper portion of this figure we have considered the case of the SS-18 missile (Y = 0.75 Mton) with a circular error probable accuracy of CEP = 0.15 nm (perhaps, in 1985?) on the Minuteman silos (H = 2000 psi). In this example, 5 of the 7 silos were destroyed under the assumption of 100% reliability for the SS-18. The same parameters are used in the lower portion of the figure (Y = 0.75 Mton, CEP = 0.15 nm), but the Minuteman silos have been hardened to H = 5000 psi; 4 of the 7 missiles were successful (with 100% reliability). If the reliability of the SS-18 had been 85%, only 6 of the 7 missiles would have landed.

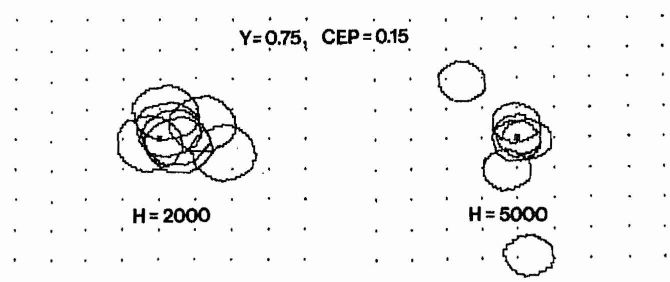

Fig. 2 HARDENED MINUTEMAN SILOS:
(Caption on previous page)

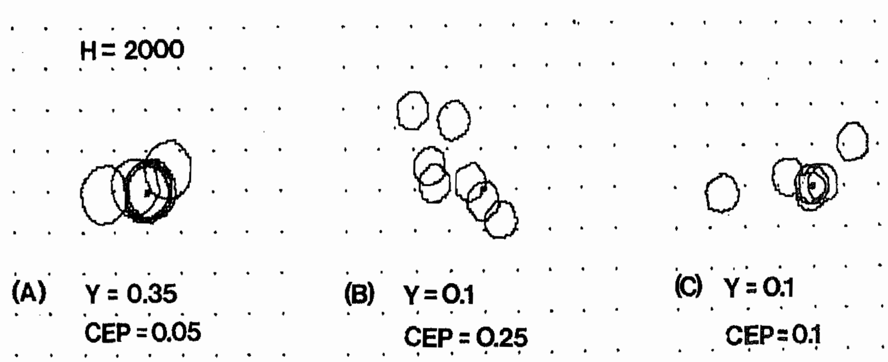

Fig. 3. U.S. COUNTER-FORCE WEAPONS: (A) The MX missile (Y = 0.35 Mton, CEP = 0.05 nm) is aimed at silos with H = 2000 psi; the smaller, but very accurate MX could be used as a first-strike weapon. (B) The Trident I missile (Y = 0.1 Mton) may have modest accuracy (middle of figure, Y = 0.1 Mton, CEP = 0.25 nm), or (C) the Trident II may have a very good accuracy (bottom of figure; CEP = 0.1 nm). The former case of 0.25 nm could imply a second-strike role against urban targets (or a first strike against an airfield), while the later case of 0.1 nm could imply a first-strike role against Soviet silos.

by increasing H from 2000 psi to 5000 psi. The ICG display in Fig. 2 shows that the consequence of this improvement are not very great. These results are consistent with the calculation of the SSKP which decreases from 65% for 2000 psi to 44% for 5000 psi for the case of R = 1.0.

III.B Counter - Force Weapons. Figure 3 shows quite graphically that the MX missile (Y = 0.35 Mt, CEP = 100 m = 0.05 nm, and let us assume H = 2000 psi for Soviet silos) is a counterforce weapon that could destroy a hardened target in a first-strike attack. In spite of the fact that the MX has a smaller yield than the SS-18 (0.35 Mt/0.75 Mt ≅ 50%), its greater accuracy (0.05 nm/0.15 nm = 1/3) allows the MX to have a considerably larger SSKP (99%) than the SS-18 (65%). Figure 3 shows that the Trident I submarine (Y = 0.1 Mt) would not be used as a first-strike weapon if its CEP = 0.25 nm because of its minimal kill ability, but that (depending on the hardness of the target) the Trident II could be a first-strike weapon if its CEP = 0.1 nm or less.

III.C Civil Defense. Lastly, one can examine the ability of warheads to destroy cities (H = 5 psi). In Figure 4 the ICG plot of a "random" attack by SS-18 warheads indicates that one warhead of 3/4 megaton can easily destroy (r_k = 6.7 km) the city in the figure (3 km by 3 km). If a civil defense policy is established to harden shelters with H = 30 psi, ICG shows that the hardened urban targets are still destroyed (r_k = 1.7 km). The hardening of cities is very difficult; hence the Federal Emergency Management Agency (FEMA) is establishing controversial evacuation plans for U.S. cities.

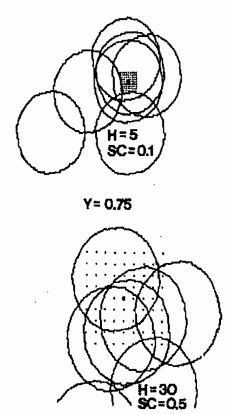

Fig. 4. CIVIL DEFENSE: Typical buildings in urban areas have a hardness of H = 5 psi; the SS-18 (Y = 0.75 Mton) can easily destroy large areas (top of figure; r_k = 6.7 km; circles seperated for visualization and a scale factor of 1:10). Using hardened, civil defense shelters (H = 30 psi) doesn't effectively mitigate the situation (bottom of figure; r_k = 1.7 km; circles seperated with CEP = 1 nm and a scale factor of 1:2).

IV. MISSILE ACCURACY AND GRAVITATIONAL BIAS ERROR

The issue of "bias error" in ICBM targeting has been raised recently[10]; it has been suggested that systematic errors from gravitational uncertainties may reduce the accuracies of US/USSR missiles so that they may not attain their stated accuracies for trajectories over the poles. (This inaccuracy is probably less than the uncertainty in the listed aim point.) This reduction in accuracy could result because the ICBM's would experience a different gravitational field for ballistic trajectories over the poles (which are not tested) as compared to the trajectory to Kwajalein Atoll (which is often tested); the uncertainties in correcting for the different "g" force for the polar trajectory (as well as other gravitational shifts) might shift the "aim point" away from the intended target in an undeterminable way. The Executive Branch has indicated that the bias errors are included in the listed accuracies of the ICBM's. However, it is important to consider the issue of gravitational bias since it questions whether either side could ever have confidence in its ability to successfully carry out a preemptive first strike. We will not be able to determine the uncertainties caused by these bias error corrections; however, we will simulate bias error with ICG in order to graphically describe the problems.

In order to avoid the mathematical complications[11] from an ICBM's Keplerian elliptical trajectory, let us consider[7] the trajectory of an ICBM that follows a parabolic path above a large flat earth. Since the earth's polar radius of 6357 km is 21 km (0.3%) smaller than its equatorial radius of 6378 km, we should expect different "g" values for the polar trajectory as compared to the trajectory to the U.S. missile target at Kwajalein Atoll. In the normal three dimensional problem one would consider the earth to be made up of a variety of "multipolar" shaped mass objects (hamburger shaped, oblate spheroidal, etc.), and then apply Newton's second law to a complicated force function which described this nonspherical, multipolar earth. We shall allow our pedagogical earth to be flat in order to estimate the uncertainty in the range

$$x = v^2 \sin(2\theta)/g \qquad (6)$$

that is caused by the uncertainty Δg in the different gravitational field of an untested trajectory. The uncertainty in the range will be

$$\Delta X/X = 2(\Delta v/v) + 2(\Delta\theta/\tan(2\theta)) - \Delta g/g. \qquad (7)$$

The difference in g between trajectories over the pole and along the equator can be approximately determined from the ratio of the mass in the bulge (ΔM) of the earth to the mass of the earth (M). For trajectories which stay reasonably close to the earth (within about 1000 miles), we can crudely approximate $\Delta g/g \cong \Delta M/M$. Since $\Delta R/R \cong 0.3\% \cong 10^{-3}$, we can expect[12] approximately that $\Delta g/g \cong \Delta M/M \cong 10^{-3}$. From this we see that the potential uncertainty in the ICBM flight path from an uncorrected gravitational bias error (10^{-3}) is considerably larger than the uncertainty in the range due to uncertainties in velocity and angles which are about 10^{-5} = (0.1 km/10,000 km). Thus, it is clear that gravitational corrections (due to a nonspherical Earth, local gravity anomalies, and the Earth's rotation) must be made for polar trajectories; the only question is the degree of accuracy with which one must be able to perform these corrections in order to reduce the uncertainty in $\Delta g/g$ to better than 10^{-5}. Since neither the US, nor the USSR will be allowed to test the quality of their calculations with ICBM launches over the pole to the territory of the other side, a government would have to believe that their aerospace experts are capable of measurements and calculations with better than 1% accuracy in the correction for the g forces in order to have any kind of confidence that a strike on land-based missile silos would have any chance of success. ICG can be used to illustrate these effects; in Figure 5 we have simulated a substantial gravitational bias error by shifting the pattern of circles from the aim point with the "joy stick" of the computer. In this figure we have set the magnitude of the bias error equal to 0.3 nm in both the x and y directions. Since the magnitude of the total bias error in this example is 0.45 nm (or three times the CEP of 0.15 nm used in this ICG example) all of the missiles (in this figure) missed the target. The actual magnitude of the inaccuracy in the bias error correction is less than this figure, but ICG descriptively indicates how small the bias error has to be in order to neglect its consideration.

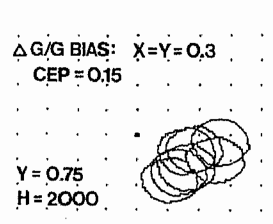

Fig. 5 GRAVITATIONAL BIAS ERROR: Corrections for different trajectories ($\Delta g/g \cong 10^{-3}$) must be carried out to about 1% if the bias error is not to degrade the CEP of missiles (CEP/Range $\cong 10^{-5}$). In Fig. 5, the aim point of the SS-18 (Y = 0.75 Mt, CEP = 0.15 nm, H = 2000 psi) was moved from the silo with a very large bias error of 0.4 nm with the "joy stick" of the computer.

V. MIRV/ASW

In this section we will briefly describe two ICG programs that were developed by Kent Norville, a student in my class on the arms race; these programs on MIRV and ASW (anti-submarine warfare) are intended to be provocative "teaching tools" rather than sophisticated "policy making tools."

The MIRV technology is capable of spreading its individual warheads over a distance of about 1000 km; the actual calculation of the elliptical, ballistic trajectories of the reentry vehicles can be approximated as a shift in the range and tracking position from the original ballistic trajectory. In order to simplify the mathematics, the program uses the "flat earth" approximation (Fig. 6) for the ballistic projectiles; the program allows the user to vary the number of reentry vehicles, and their individual velocities (magnitude and angle) with respect to the bus. This approach allows only a variation in the range direction, and not the tracking direction; nevertheless, this approach has assisted those students who are unfamiliar with MIRV to understand it more completely.

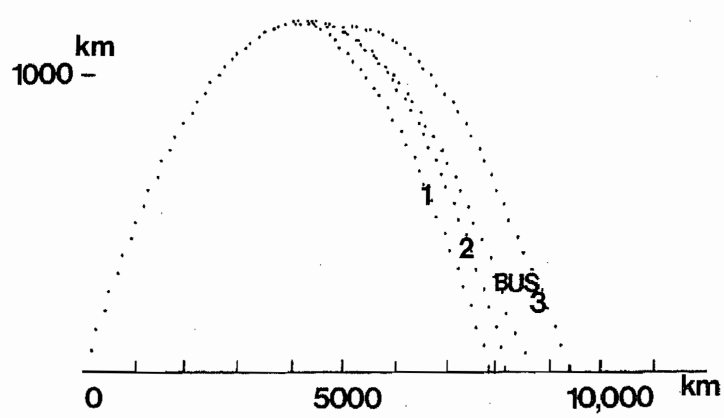

Fig. 6. MIRV: The equations for the "flat earth" (Sec. IV) are used to obtain the trajectories for the individual reentry vehicles and the missile bus. An initial velocity of 10^4 m/s is used for the ICBM. The number of reentry vehicles and their velocities and angles (in range only) can be varied in the program. Momentum is conserved in the system as the reentry vehicles are released. The range, height and spread in range for the re-entry vehicles from the "flat earth" calculations are very similar to those for the actual "round earth."

The ICG program "ASW" applies an ASW technology that determines the position of a submarine by comparing the time delays of signals reflected from a submarine to several hydrophones; more recent technologies[13] use sonobuoys that transmit and receive their own sonar signals, infrared observations from satellites, Fourier transforming sonar signals, lasers, and other technologies. The "ASW" program stimulates consideration of these more modern technologies as well as making clear the uniqueness of the ocean-going leg of the triad.

VI. FIRST STRIKE

The question of vulnerability to a first-strike is continually being debated. The issue of "vulnerability" usually means "will we have enough nuclear weapons to assure destruction on those who would attack us." The debates on this issue often use words like "superiority, parity and sufficiency." In spite of the fact that the uncertainties in first-strike situations are likely to be greater than the certainties, both sides in this debate do use numerical data to buttress their arguments. (For example, it would be difficult to quantify the uncertainty in the command, control, and communications systems caused by the electromagnetic pulse.)

If one chooses to answer these questions with numbers and equations, one soon learns that the size of the data base, and the complexity of the manipulations, requires a computer; it is for this reason that we have developed the program "First-Strike." This program analyzes the strategic balance by letting us vary 90 adjustable parameters to explore how the many parameters affect the question of vulnerability. Each side (America = A and Russia = R) has a 6 by 6 matrix of parameters to describe their weapon systems. The matrix formulation is merely a way of keeping track of the parameters; we do not use matrix algebra. Three data sets (the present, the future without arms control, and the future with arms control) are included with the program. Table I shows the A and R matrices as they approximately appear at the present time (1980-85):

Table I. The A and R matrices for the present time (1980-85). The rows are the 6 different missile classes (land, sea, air, intermediate range ballistic missile, tactical weapons, and cruise missile). The columns are the average values of the parameters which describe each system (yield, average number of reentry vehicles per launcher, number of launchers, circular error probable accuracy (nautical miles), reliability (0-1), silo hardness (psi)).

AMERICAN A MATRIX (1985??) RUSSIAN R MATRIX

	1=Y	2=M	3=N	4=CEP	5=R	6=H	1=Y	2=M	3=N	4=CEP	5=R	6=H
1=LAND	.335	2.1	1052	.12	.8	2000	.75	3.2	1398	.15	.7	2000
2=SEA	.1	8	656	.25	.8	5	.5	2	950	.5	.7	5
3=AIR	1	4	346	.1	.8	3	1	4	156	.1	.8	3
4=IRBM	.1	1	1500	.1	.8	5	.1	1	4500	.1	.8	5
5=TAC.	.02	1	20000	.1	.8	5	.02	1	10000	.1	.8	5
6=CM	.2	1	1000	.01	.8	5	0	0	0	.01	0	0

This data set can be updated easily to account for changes in the parameters. For example, we might want to take into account that the 52 Titan ICBM's are being decommissioned; by typing 1,3 (row,column), and 1000, we will have changed the number of American land-based missiles from 1052 to 1000. If we are content with the data set, we would type 0,0 to accept it. One can easily take issue with the averaging process that we have used; for example, we have properly taken into account the MIRVing of Minuteman (II, and III) by using M = 2.1, but we have further assumed that they will have an average yield comparable to the Mark 12-A warheads of 335 kilotons. The main point of "First-Strike" is to create a method of changing the parameters as one discusses (and updates) the data base; after the data base is acceptable to the debators, the numerical operations can be carried out. In addition, there are other parameters which deal with the number of warheads sent to attack a silo (L), gravitational bias error (BE = CEP(with)/CEP(without)), submarine duty factor, effectivness of ASW, and various other parameters.

One can examine the one-on-one match-ups between various systems by calculating the single shot kill probability (P in Section II) with reliability ($T_k = R \times P_k$), and then the kill probability with L warheads (from seperate missiles),

$$K_p^L = 1 - (1 - T_k)^L \tag{8}$$

After we have examined these initial one-to-one results, "First Strike" matches up the land-based missiles against each other. In the example discussed below we have used 2 warheads (L = 2) against each silo. In the next version of this program, we intend to add further flexabilities[6] to allow any system to attack any other system, to allow for the attack of cities, and to allow for a "launch on warning" situation and other operational factors.

We have allowed for broad uncertainties in "First Strike" by allowing for fractional (0-1) parameters; for our "base case" we have used the following:

FSUB = submarine duty factor = 0.6 for A; 0.2 for R.
FASW = effectiveness of ASW = 0.5 for A and R.
FIRBM = FTACTICAL = FCRUISE = FBOMBER
= fractions destroyed = 0.5 and 0.5 for A and R.

It would not be difficult to show that all the parameters (other than FSUB) should be smaller than 0.5; thus, the destructiveness of the results from "First Strike" are actually an upper bound estimate. The number of surviving launchers are merely the products of the appropriate fractional probabilities and the number of launchers, except for the case of an attack on the land-based missiles where we have used the probability formulation from Eq. 2 and 8. The resultant numbers of remaining warheads after a first strike were obtained from the base case of the "present" data set and they are displayed in Fig. 7. We see that approximately 50% (an upper bound) of the first triad (land/sea/air) and the second triad (IRBM/tactical/cruise missile) would be destroyed[14] if either side should be tempted to carry out such a scenario. Since the number of warheads surviving would be rather large, there is still a large second-strike force to retaliate. Since the fractional probabilities are not certain; debators can change these parameters on the next run of the program. "First Strike" also keeps track of the total yield, lethality (K), and the numbers of launchers before and after.

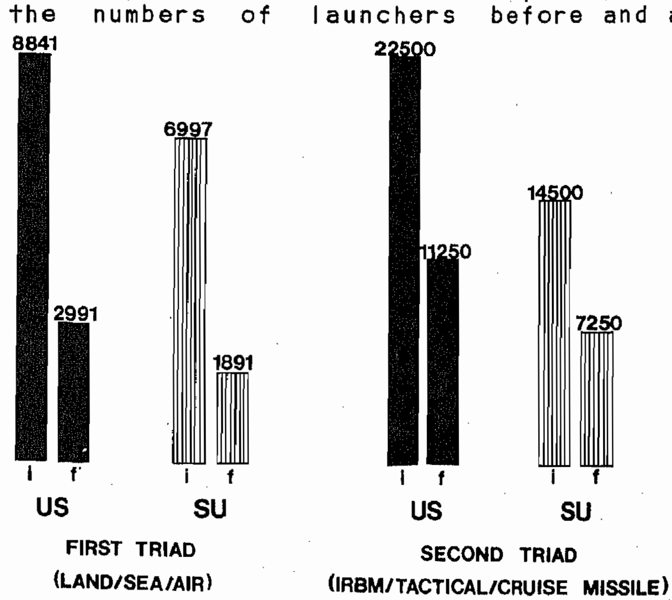

Fig. 7. FIRST STRIKE: The number of US/USSR warheads are compared before and after a "first strike." The present (1980-85) data base and the parameters described in the text were used to obtain these results.

VII. FALLOUT.

If a nuclear attack ever occurred, there would be radioactive plumes extending from the target points. The ICG program "Fallout" calls up a map of the United States (Fig. 8) and allows the user to locate the targets and the number of weapons used on each. Parallelograms are used to simulate the more complex shapes[15] of the plumes; the area of the parallelograms agree with the more accurately calculated affected areas by about 25%. The final shapes for the plumes are highly dependent on the wind velocities; our ICG program allows for two different wind velocities, 20 mph and 60 mph where the later is approximately 50% of the stratospheric velocity. Two plumes are located at each target; the inner plume represents a minimum dose of 1350 REM outside of buildings and 450 REM inside the building; the outer plume represents 450 REM outside and 150 REM inside. These dose levels would vary considerably within the plumes and within the buildings. A radiation dose of about 450 REM would kill about 50% of the population. The present version of this program does not determine the number of fatalities; a future version will include population density and a biological coupling factor in order to do this even though there would be great uncertainties in the absolute numbers of fatalities.

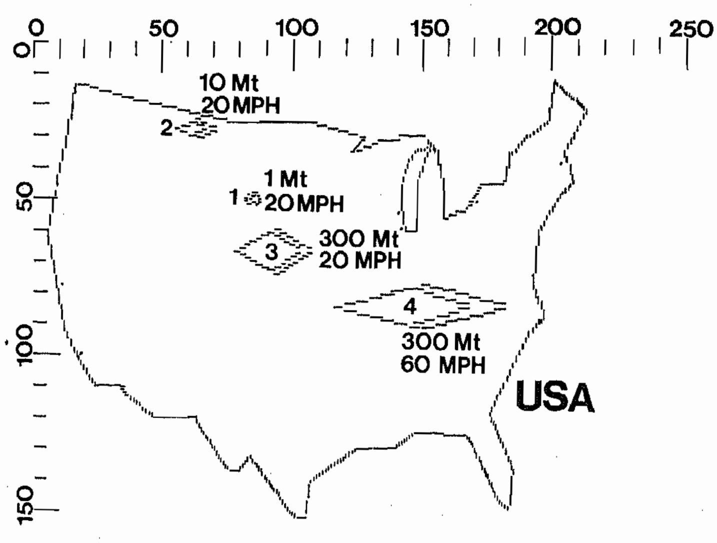

Fig. 8. FALLOUT: (Figure caption on next page.)

Fig. 8. FALLOUT: Four different attacks are considered with "Fallout;" (1) one megaton weapon (50% fission), (2) 10 one megaton weapons, (3) 300 one megaton weapons with a wind velocity of 20 mph, and (4) 300 one megaton weapons with a wind velocity of 60 mph (about 50% of stratospheric velocity). The inner plume represents an area in which a minimum dose of 1350 REM is received for those who are outside of buildings, and a minimum dose of 450 REM inside of buildings; the outer plume represents an area with a dose of 450 REM outside and 150 REM inside. The bases attacked are (1) Ellsworth (x=82,Y=50), (2) Malmstrom (55,28), (3) Warren (78,67), and (4) Whiteman (115,85).

VIII. DIGITAL IMAGE PROCESSING.

In order for the Senate to ratify an arms control agreement, it must have confidence in its "national technical means" to verify that the various conditions of the treaty are being upheld by the other party. Ultimately, the Senate must decide how likely it would be that the other party could carry out a significant infraction (in terms of national security) before we could discover the infraction. One of main techniques for verification is photography from spy satellites. The information in the photographic images can be enhanced by digitizing the intensity at various regions of a photograph; the digitization is followed by mathematical operations[16] on the digital information in order to enhance the signal with respect to the background noise. More recently it has become possible to directly process the electronic output of a charge-coupled device (CCD)[17] without the necessity of using film; the CCD devices are much more efficient than film, have a broader spectral range (into the infrared), and can be used directly with computers without requiring digitizing that is needed for film. In addition the CCDs are preferable to vidicon television techniques since they can have better resolution, can be operated with low voltages, and are more resilient under impact. Some commercial CCDs contain 640,000 regions (pixels) of digital information; a pixel region can be about 15 microns on a side. CCD cameras are presently commercially available (Micron Technology, Boise, Idaho for about $300) that can be used with Apple computers (54,000 pixels). The techniques of digital image processing (DIP) have been used in a wide variety of applications beyond verification such as in astronomy, medicine, geology, and criminology.

On balance, the "spy satellites" and DIP are thought to be stabilizing for the arms race because they (1) enhance verification giving greater confidence to the SALT/START process, and (2) because more information from satellites can reduce the tendency towards "worst

possible case analysis." Some Senators objected to SALT II because of the loss of verification facilities in Iran. President Johnson made the comment in 1967 when he indicated that the $35-40 billion spent on space was worth it because "I know how many missiles the enemy has."

This section of our paper will do the following: (1) Briefly discuss some mathematical applications of DIP, and (2) demonstrate some initial results of CCD with Apple computers. In Fig. 9 we have created a one dimensional silo (20 pixels wide) that is partially blurred by noise developed from a random number generator. When the signal-to-noise ratio (S/N) is very high, one does not need to process the data to see the silo, but when the S/N ratio is less than one it becomes necessary to process the image in order to be able to "see" the silo. In Fig. 9, we have subtracted the image from a version of the same image that has been shifted by 1 to 20 pixels. This technique allows us to examine the data for an auto-correlation within the data; if we expect the silo to be 20 pixels wide, we would look for a figure that looks like a square wave with a wavelength of 40 pixels. In order to work with lower S/N ratios, one could then Fourier analyze the difference image and look for Fourier components consistent with the size of the silo.

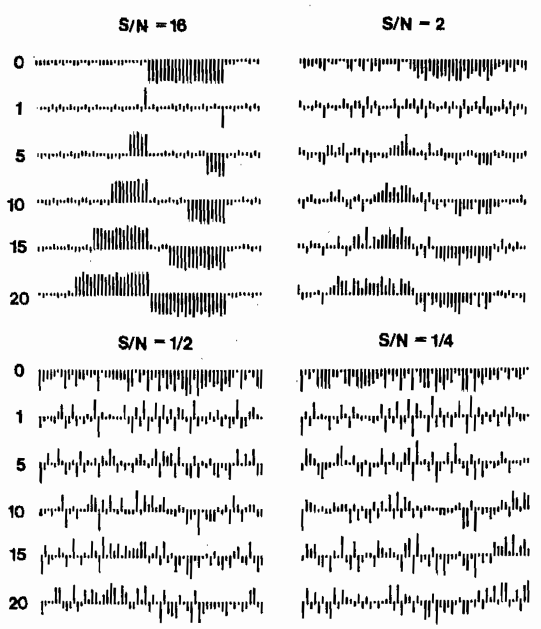

Fig. 9. DIGITAL IMAGE PROCESSING: A random number generator is used to partially mask a missile silo with S/N ratios between 16 and 1/4. The silo (20 pixels wide) can be discovered with auto-correlation techniques by subtracting the data from the original data after shifting it by 1 to 20 pixels. If the resulting data was Fourier analyzed, one would obtain a strong component with a 40 pixel wavelength.

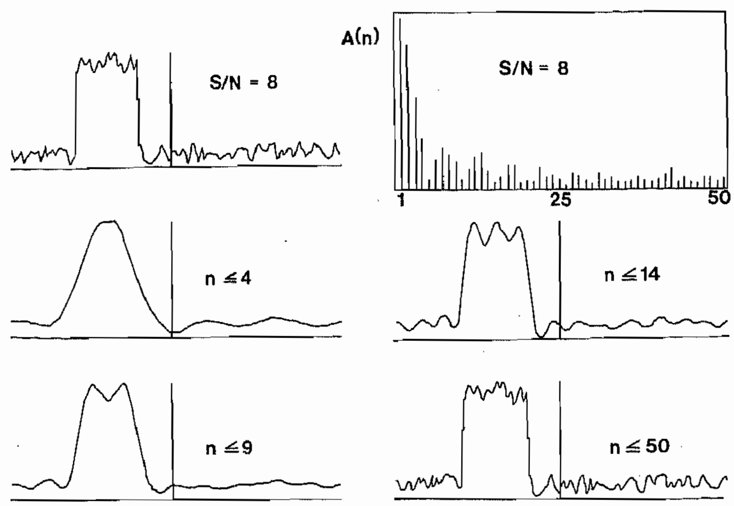

Fig. 10. FOURIER TRANSFORM: The spatial data can be Fourier analyzed to obtain its fequency spectrum; by reversing the process the spatial representation can be reestablished. The silo appears more clearly when only the 4 lowest frequency components are used and the 46 higher components containing the "noise" are rejected.

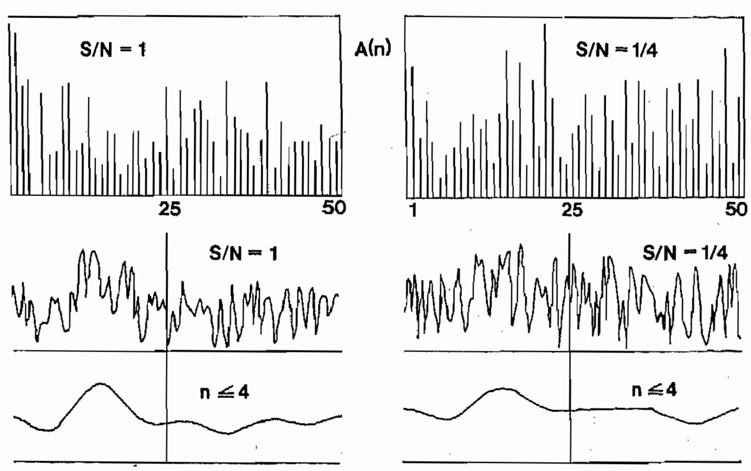

Fig. 11. S/N RATIO. The approach of Fig. 10 successfully identifies a silo with a S/N of 1/4. Two dimensional transforms would use the geometry of the silo to improve the results.

Another approach of DIP is to Fourier transform the digital information of the image, remove the high frequency components that are associated with the noise, and then Fourier transform the remaining low frequency (long wavelength) signal back to the spatial image. By analyzing the data we convert it from a spatial representation to a freqency spectrum; the second Fourier transform then synthesizes (reconstructs) the spatial image from the truncated frequency spectrum. In Fig. 10, we have obtained a 101 pixel array in one dimension from the equation y = (NN)(Rnd(1)) + S where NN is the peak noise and S is the intensity of the signal. The image in Fig. 10 has a favorable signal-to-noise ratio of S/N = S/(NN/2) = 8; when this image is Fourier analyzed, one obtains large components in the low frequency region which is associated with the silo signal, and small components at the high frequency region which is associated with random noise. When the image is reconstructed from these components, we observe that only the 4 lowest components are necessary to easily detect the silo, and that a greater number of components tends to blurr the reconstructed image. In Fig. 11 we have increased the noise level to give S/N = 1/1 and 1/4; the reconstructed images with the lowest four components clearly show the location of the silo. These examples must next be extended to the regime of two dimensions; the convolution theorem must be applied to remove distortion by the viewing system. Other transforms can be used in order to apply mathematics that is more "tailor-made" to the geometry of the object. Finally, we have obtained some grey level presentations of pictorial images by using a charge-coupled device, an opticRAM with 128 x 256 pixels. The grey levels in the final picture are obtained by comparing images of the same object that were obtained with different exposure times. Since the cost can be as low as 3 cents/pixel, it is clear that the CCD technology will have a tremendous impact on verification and digitial image processsing.

IX. THE SCIENCE AND SOCIETY PUBLIC POLICY DISKETTE

A diskette and manual of 15 programs is available from us (553 Serrano, San Luis Obispo, CA 93401) on a nonprofit, noncopyright basis for $10. Please send us your results for possible inclusion on future diskettes so that we can create an imformation network. I would like to thank James Hauser, Fred Jaquin, Alan Lyon, Kent Norville, Dietrich Schroeer, and Walt Wilson for assistance on this project.

REFERENCES

1. R. Sperry, Science 217, 1223 (1982).

2. T. Graedel and R. McGill, Science 215, 1191 (1982).

3. R. Myers, Microcomputer Graphics, Addison-Wesley, Reading, MA, 1982.

4. M. Brode, Ann. Rev. Nuc. Sci. 18, 153 (1968).

5. K. Tsipis, Science 187, 393 (1975); 206, 510 (1979).

6. J. Steinbruner and T. Garwin, Int. Sec. 1, 138 (summer, 1976).

7. D. Hafemeister, Am. J. Phys. 51, 215 (1983).

8. P. Nitze, Military Implicatons on the SALT II Treaty, U.S. Senate Armed Services Comm., Washington, D.C., 1979, p. 891.

9. S. Glasstone and P. Dolan, The Effects of Nuclear Weapons, Dept. of Defense and Dept. of Energy, Washington, D.C., 1977.

10. E. Marshall, Science 213, 1230 (1981). J. E. Anderson, Bull. At. Sci. 37, 6 (Nov., 1981).

11. D. Hoag, p. 19 in Impact of New Technologies on the Arms Race, Ed. by B. Feld, T. Greenwood, G. Rathgens, and S. Weinberg, MIT Press, Cambridge, MA, 1971.

12. W. Kaula, Theory of Satellite Geodesy, Blaisdell, Waltham, MA, 1966. M. Caputo, The Gravity Field of the Earth, Academic, NY, 1967.

13. K. Tsipis, A. Cahn, and B. Feld, The Future of the Sea-Based Deterrent, MIT Press, Cambridge, MA, 1973.

14. R. Forsberg, Sci. Am. 247, 52 (Nov., 1982).

15. S. Drell and F. von Hippel, Sci. Am. 235, 27 (Nov., 1976). K. Lewis, Sci. Am. 241, 35 (July, 1979). S. Fetter and K. Tsipis, Sci. Am. 244, 41 (April, 1981). The Effects of Nuclear War, Office of Technology Assessment, Washington, D.C., 1979.

16. B. Hunt, Chapter 6 of this book.

17. J. Kristian and M. Blouke, Sci. Am. 247, 67 (Oct., 1982).