Ballistic Missile Proliferation Among the "Axis of Evil":

Iran, Iraq, North Korea and Pakistan

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Introduction

The proliferation of ballistic missiles is a growing threat in these troubled times. The range of these weapons and the aggressive nature of their targeting makes them destabilizing forces in already sensitive regions. Missile deployment on both sides of conflicts in the Middle East, the Indian subcontinent, and the Korean peninsula is a significant cause for concern for everyone interested in global security.

Open source discussion about foreign missiles typically includes an estimate of their theoretical range, often superimposing this range over a map of the region, displaying the threat posed to neighbors. Missile ranges are inherently political, serving to inflame public opinion on the threat posed by a neighbor, or scare an adversary into backing down by targeting his capital. As a student of aeronautical engineering, I have the skills and interest to determine accurate missile ranges, lifting the political pall from the discussion. Because little technical information is freely available, this analysis will require simplifying assumptions, and the application of real world constraints to theory.

Missile range analysis is an engineering challenge with significant relevance to current events and the threat of weapons of mass destruction. Much political noise has been made in recent years about the ballistic missile threat from North Korea and other members of the “Axis of Evil.” A sober technical evaluation of the actual ranges attainable with current technology by these countries will bring the threat into perspective. Given the staggering amounts of money spent on National Missile Defense, this type of analysis is invaluable in understanding threat levels and setting national priorities. I hope that cooler heads will prevail in the future, aided by realistic numbers and an understanding of the limits of theoretical models.

History

Like all difficult technical problems, even top secret missile designs cannot be developed in a vacuum.[1] The genealogy of the ideas present in current North Korean missile designs can be traced to the beginning of the missile age with the German V-2, through refinement by Soviet missile designers, and modification by Iraqi and North Korean engineers. These developments have increased range at the cost of structural strength and reliability. The "Axis of Evil" still relies heavily on foreign assistance, and does not yet have a native design capability.

German Origin

First developed in 1939, the V-2 marks the beginning of the missile age, and elements of its design still persist in modern systems. The basic design, with gyroscopic guidance and aerodynamic steering by fins and vanes, remain unchanged in derivative designs. The distinctive body shape, now recognized as Tintin's moon rocket, has been smoothed and the body lengthened. The design by von Braun was not initially focused on saving weight, and the structure was significantly overbuilt.[2] However, in an age before computational methods, this approach makes sense. The fuel, a 75% mix of ethanol and water, combined with liquid oxygen, provided a specific impulse of 210 seconds. Specific impulse is a measure of efficiency, the fuel exhaust speed divided by gravity, with higher values indicating less propellant is required to achieve a similar momentum increase.

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[1] Pun intended

[2] T.D. Dungan, *V-2: A Combat History of the First Ballistic Missile*, Westholme Publishing, 2005.

Accuracy was limited by the inertial guidance to 17 km,[3] good enough to target a city, but not anything more specific. Despite firing over 3,000 weapons at Belgium, France and Britain, the Germans succeeded at killing only 2,754 civilians and injuring 6,523 others.[4] However the supersonic impact velocities prevented any forewarning of an attack, making the true effectiveness of the weapon psychological, not military.

Russian Refinement

After the end of the Second World War, both American and Soviet forces rushed to capture German rocket scientists. Von Braun and others from Peenemünde were sent to Huntsville AL. There they developed the Redstone, setting the basis for the American manned space effort. The scientists captured by the Soviets were sent to Kapustin Yar, where they rebuilt copies of the V-2, dubbed the R-1.[5] Once their knowledge was transferred to Soviet engineers, the German scientists were repatriated in the 1950's. The R-2 improved the original design by increasing the length by four meters, replacing the fuel with methyl alchol, and increasing the range to nearly 550 km.[6]

The first major native Soviet advance was a new engine design by Aleksei Isayev, which replaced the complex and heavy German design with a single copper walled combustion chamber and a flat plate injector. This simplified the "plumbing nightmare" of the V-2, which had separate fuel lines to each sprayer.[7] The R-11 was

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[3] T.D. Dungan, *V-2: A Combat History of the First Ballistic Missile*, Westholme Publishing, 2005.

[4] Peter Risby, "Air Raid Precautions - Deaths and Injuries," http://myweb.tiscali.co.uk/homefront/arp/arp4a.html

[5] Victor Antanovich, "Testing of the A-4 Rocket in Kapustin Yar," http://www.russianspaceweb.com/kapyar_a4.html

[6] Charles Vick, "R-2 / SS-2 Sibling", GlobalSecurity.org, http://www.globalsecurity.org/wmd/world/russia/r-2.htm, April 25 2005.

[7] Mark Wade, "R-11", Encyclopedia Astronautica, http://www.astronautix.com/lvs/r11.htm,

flight tested in 1953 and deployed in 1955. The design initially used kerosene, but that fuel did not perform as well as expected, and was replaced by unsymmetrical dimethyl-hydrazine (UDMH) in future models. The oxidizer was changed from liquid oxygen to red-fuming nitric acid (RFNA).

The final Soviet refinement, the R-17, reduced the range to 300 km, and was exported around the world as the Scud. The change to UDMH, a storable propellant, allowed the missile to be mounted on truck-based launchers. This mobile base makes the missile much more resistant to destruction by enemy air power. The guidance of the Scud was upgraded to include optical corrections, but accuracy was still limited by the fact that the warhead remains attached to the missile. With this large vehicle undergoing reentry without any propulsion in the terminal phase, the accuracy diminished with increasing range, never better than 1 km.[8]

Iraqi Lengthening

Iraq acquired the Scud design in the 1970's [9] and set about lengthening the missile for improved range, with the goal of hitting Tehran, 600 km from Baghdad. Because the higher quality UDMH fuel was not available, and petroleum products were easily obtainable, the Iraqi engine design used kerosene.[10] The lengthening process decreased the structural mass fraction from 18% to 14% and limited the payload to 500 kg. Without access to sophisticated alloys, the Iraqi structural modifications made the missile fragile

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[8] Charles Vick, "R-11 / SS-1B Scud-A", GlobalSecurity.org, http://www.globalsecurity.org/wmd/world/russia/r-11.htm. April 28 2005.

[9] Carus, Seth W. and Joseph S. Bermudez, Jr., "Iraq's Al-Husayn Missile Programme," *Jane's' Soviet Intelligence Review,* May 1990, p. 204.

[10] Bernard Rostker, "Information Paper: Iraq's Scud Ballistic Missiles," Office of the Special Assistant for Gulf War Illnesses, US Department of Defense, http://www.gulflink.osd.mil/scud_info/scud_info_s02.htm, July 25, 2000.

on reentry, and the missile often tumbled and disintegrated before hitting the ground.[11] In addition to making it difficult to intercept with the Patriot anti-missile system, this instability greatly diminished the accuracy of the al-Hussein. A shorter variant was produced with the hope of increasing accuracy while maintaining range, but it was not produced in any significant quantity.

Iraq launched 361 Scud-B and 117 al-Hussein missiles at Iran during their ten year war, killing perhaps 2000 civilians.[12] As with the German experience, even though the weapons were not individually effective, the psychological impact of the attacks was significant, causing the evacuation of a quarter of the population of Tehran. Iran came to realize the usefulness of this type of weapon, and began to acquire its own versions from an indiscriminate vendor, North Korea.

North Korean Development and Export

An isolated regime, missile exports form a large part of the North Korean economy. The sole operating Scud manufacturing plant exists in North Korea, and continues to churn out 1960's era technology. North Korea continues to acquire foreign designs and attempts to develop native expertise. However, most North Korean designs seem to involve purchasing a new engine type and stacking several smaller missiles on top of it, in a crude version of staging. These interstage connections are often the source of accidents in their flight tests, revealing that the program is still dependent on foreign assistance.

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[11] Bernard Rostker, Section 4, "Iraq's Use of Scuds During Operation Desert Storm."

[12] Jane's Intelligence Review, "Strategic Delivery Systems," http://www.fas.org/news/iran/1995/iran-950611.htm June 1, 1995, p 18.

Moving forward from the Scud design, North Korea acquired the Russian SSN-5 design, forming the basis of the Nodong primary stage. The SSN-5 is a submarine launched missile with a more modern engine by the Isayev design bureau. In the aftermath of unemployment caused by strategic arms control treaties, many Russian missile designers went to work for North Korea, exporting their knowledge if not actually emigrating. The Nodong reflects modern Soviet designs, including a solid charge to start the turbo-pumps,[13] replacing compressed gas tanks from the V-2 era. Further developments progressed from the Russian SSN-5, using four nozzles for increased performance. This is a simple way of improving thrust without requiring significant redesign. The Nodong's second stage is a modified Scud with a releasable warhead. The reentry vehicle is unguided, but releasing the missile body should avoid the tumbling phenomenon, markedly improving accuracy.

The three stage Taepodong-1 uses the Nodong first stage, a Scud second stage, and adds a small Soviet Tochka/SS-21 motor for the third stage, probably acquired from Iran.[14] This missile was flight tested in August 1998, launching south from Musudan-ri and over Japan. Official North Korean sources claimed that the launch had placed a satellite into a highly eccentric orbit (6,978 km by 219 km), but U.S. government and amateur tracking stations discredit this claim entirely.[15] It is likely that the third stage failed to ignite, causing the loss of the satellite. It is unknown whether the booster spun

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[13] GlobalSecurity.org, "No-dong 1 Design Heritage," http://www.globalsecurity.org/wmd/world/dprk/nd-1-hist.htm

[14] Center for Nonproliferation Studies, "Paektusan-1 Space Launch Vehicle: Technical Assessment," http://www.nti.org/e_research/profiles/NK/Missile/1709_1713.html, May 2003.

[15] CNS, "Paektusan-1 Space Launch Vehicle: Technical Assessment," May 2003.

up for stabilization as designed. Debris was spread from 1,000 to 3,000 km downrange.[16]

For the improved Taepodong-2 design, North Korea use what appears to be a Chinese CSS-2 as the primary stage, and a Nodong second stage. Some sources indicate that the first stage is a cluster of four Nodong thrust chambers with shared turbo-machinery.[17] In either case, this primary stage provides significantly more thrust than a single Nodong, and makes increased ranges possible. Some in the defense community have warned that the TD-2 could hit much of the US in a three stage variant[18], but these estimates assume a much higher level of North Korean structural and reentry technology than has been observed.

A widely reported test on July 4, 2006 resulted in the successful launch of four Scud and two Nodong missiles, and the near-total failure of a Taepodong-2. The first stage failed 42 seconds into flight,[19] yielding little useful data for technical analysis. However, media reports that Iranian officials were present at the launch reveal continued cooperation between foreign governments on the missile program.

Indeed, foreign cooperation has been essential to North Korean development. After selling the Nodong and Taepodong-1 to Pakistan, which rebranded them the Ghauri-1 and Ghauri-2, North Korea received technical support for its nuclear program,

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[16] Joseph S. Bermudez, "North Koreans Test Two-Stage IRBM Over Japan," *Jane's Defense Weekly*, 9 September 1998, p.26.

[17] GlobalSecurity.org, "Taep'o-dong 2," August 2, 2006, http://www.globalsecurity.org/wmd/world/dprk/td-2.htm.

[18] Vice Admiral Lowell Jacoby, U.S. Navy, Director, Defense Intelligence Agency, Testimony to Senate Armed Services Committee, February 6 2005. http://www.armscontrolwonk.com/568/jacoby-claims-north-korea-can-arm-taepo-dong-2-with-nuke

[19] Stephen Hildreth, "North Korean Ballistic Missile Threat to the United States," *Congressional Research Service*, RS21473, October 18, 2006. http://www.fas.org/sgp/crs/nuke/RS21473.pdf

probably in the form of uranium centrifuge designs, or even actual centrifuge rotors.[20] North Korea also received flight data from tests of the Ghauri systems, circumventing their self-imposed moratorium on missile tests. Many visits occurred between high-level officials of the two countries, including 13 visits by A.Q. Khan in the 1990's, and one by then-Pakistani Prime Minister Benazir Bhutto in December 1993.[21]

North Korea has also sold full missile systems to Iran. Most of Iran's Scuds used in the Iran-Iraq war were procured from North Korea.[22] The Shahab-3, -4, and -5 are little more than renamed Nodong, Taepodong-1 and -2 missiles, respectively. The Shahab-6 appears to be a satellite launcher variant of the TD-2.[23] If these missiles attain the claimed ranges, they could threaten all of the Middle East and much of Western Europe.

With this historical development and widespread proliferation in mind, I will now proceed to a technical analysis of these V-2 derived missiles. Because the Ghauri and Shahab do not represent independent systems, they will be combined with an analysis of their North Korean sources.

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[20] Sharon Squassoni, "Weapons of Mass Destruction: Trade Between North Korea and Pakistan," *Congressional Research Service*, RL31900, October 11, 2006. http://www.fas.org/sgp/crs/nuke/RL31900.pdf, p 7.

[21] Daniel A. Pinkston, "When Did WMD Deals between Pyongyang and Islamabad Begin?" *Center for Nonproliferation Studies*, October 21, 2002, http://cns.miis.edu/pubs/week/021028.htm.

[22] Unpublished paper by Joseph S. Bermudez, Jr., "DPRK-Pakistan Ghauri Missile Cooperation," 1996.

[23] Charles Vick, "Iran Missiles," GlobalSecurity.org, October 12, 2005. http://www.globalsecurity.org/wmd/world/iran/missile.htm

Analysis

Building on summer research I performed at the GlobalSecurity.org think-tank under John Pike, I wrote software to simulate ballistic missile flight from launch to impact, taking atmospheric drag and other real world engineering effects into account. This method is preferable to an ideal assessment based solely on the rocket equation and Newton's equations of motion, as the real world is significantly more complex. The simulation does not include effects such as re-entry instability, the realities of nozzle expansion, or the earth's rotation.

Assumptions

Choosing a level of complexity that would make the simulation both achievable and accurate required some assumptions. First, neglecting the rotation of the earth makes the underlying equations significantly more simple, at the expense of minimal loss of simulation fidelity. Because the simulation will only deal with ballistic flight, and is not concerned with reaching orbit, the complexity introduced by is not worth the extra accuracy gained.

Determining parameters that define atmospheric drag was more of a challenge. Drag is dependent on frontal area, air density, velocity squared, and the non-dimensional drag coefficient. The US Standard Atmosphere[24] provides a piecewise relationship between density and altitude. NASA's FoilSim educational software[25] provides expressions for temperature and pressure versus altitude, which are needed to deter-

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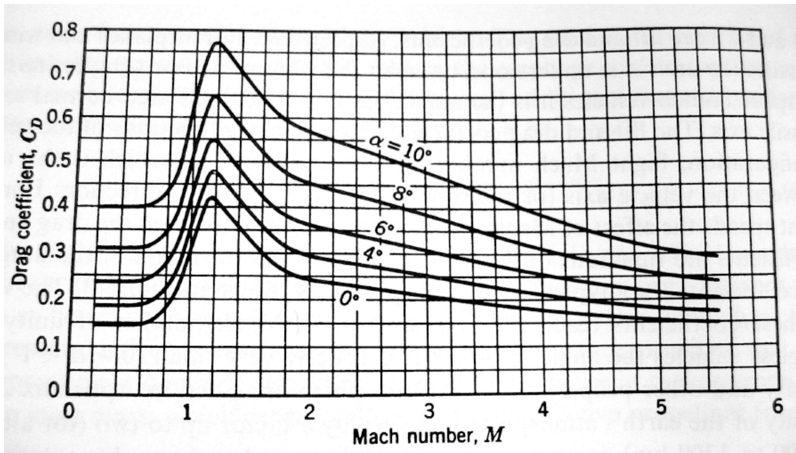
[24] U.S. Standard Atmosphere, U.S. Government Printing Office, Washington, D.C., 1976. http://modelweb.gsfc.nasa.gov/atmos/us_standard.html

[25] Tom Benson, FoilSim II Version 1.5. NASA Glenn Research Center. 2006. http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmet.html

mine the speed of sound and hence Mach number. The drag coefficient was found using data for the V-2, dependent on Mach number and angle of attack, shown below.[26]



Using the curve for zero angle of attack, which is typical for a wingless vehicle, I extracted several linear functions, operative over the span of flight Mach numbers. These functions may not be as realistic for newer body types[27], as the V-2's distinctive curved shape was designed long before modern computational fluid dynamics reduced drag considerably. A suitable alternative is to use an expression for the drag coefficient of a blunted cone,[28] ignoring the effects of supersonic flight and wave drag. However, because the nozzle exhaust flow fills the body cross section, wave drag at the aft of the vehicle is minimal.[29] Therefore, Regan's expression is suitable, provided that numbers for nose cone half angle and nose bluntness can be determined from open source missile diagrams.

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[26] George Sutton, Oscar Biblarz. *Rocket Propulsion Elements,* 7th edition, John Wiley & Sons, 2001, p 108.

[27] Robert Stein, John Kantelis, and Peter Zimmerman, "Response to *Science and Security* Article 'Technical Debate over Patriot Performance in the Gulf War' ", *Science and Global Security,* Volume 8:2, 1999, p 258.

[28] Frank Regan, *Re-Entry Vehicle Dynamics,* AIAA Education Series, American Institute of Aeronautics and Astronautics, 1984, p 230.

[29] Professor Alan Epstein, Lecture on Rocket Propulsion, MIT Course 16.50, Fall 2006.

Another source of inaccuracy lies in the dynamics of the rocket nozzle itself. Nozzles are designed to be ideally expanded at a particular altitude, with inefficiencies due to expansion shocks and flow separation at altitudes higher and lower than the design point. This can be modeled with sufficient knowledge of the nozzle: particularly exit area, throat area, exit pressure, and chamber pressure. Obviously, this information is not available for the types of missiles we wish to analyze, so simplifying assumptions are necessary.

In my work with Charles Vick at GlobalSecurity.org, he recommended using the thrust versus altitude curve from Saturn V launches to derive a reasonable model for other engine types. While it makes me uneasy to blindly apply a polynomial fit curve from an advanced American engine such as the J2 to the Scud engine, it is probably more realistic than assuming detailed knowledge about the nozzle design. Additionally, the amount of time spent in thrust is minimal compared to the total flight time, and the percent increase over ideal thrust hits a maximum of 19% over sea level when the vehicle is in vacuum. Comparing this increase to that calculated with perfect knowledge of the nozzle design, the increase seems reasonable.

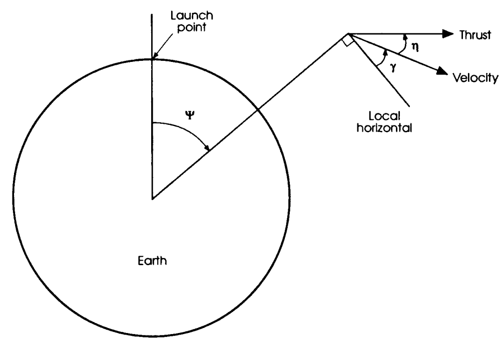
Governing Equations

The equations governing the simulation are all first order differential equations, making a closed-form solution for range infeasible. Instead, the Runge-Kutta-2 method was used to integrate numerically. The equations and variables involved are as follows:

$$\frac{dV}{dt}=\frac{T}{m} - \frac{C_d \varrho V^2 A}{2m} - g\sin(\gamma) \qquad \frac{d\gamma}{dt}=\frac{d\psi}{dt} - \frac{g}{V}\cos\gamma$$

$$\frac{d\psi}{dt}=V\frac{\cos(\gamma)}{R_e+h} \qquad \frac{dh}{dt}=V\sin(\gamma) \qquad \frac{dm}{dt}=\frac{T}{g_0 I_{sp}}$$

V: velocity in direction of travel [m/s]
T: thrust [N], aligned with velocity, η = 0
m: mass [kg], stages are dropped when fuel is exhausted
Cd: drag coefficient [dimensionless]
A: missile frontal area [m^2]
ϒ: flight path angle [rad], relative to local horizontal
ψ: range angle [rad], defined to zero at launch point
ρ: air density [kg/m^3]
h: altitude above Earth surface [m]
Re: Earth radius, 6,370,000 [m]
g0: 9.8066 [m/s^2], varies with altitude
I_{sp}: fuel specific impulse [sec]



These equations were taken from Thompson's *Introduction to Space Dynamics*[30], as well as source code by Dr. David Wright, at the Union for Concerned Scientists.[31] They are in a form designed for the rocket to be pulled over by gravity. While the vehicle is launched vertically, the optimum launch angle to achieve a desired range can easily be calculated.[32] I assume that the vehicle remains vertical for the first five seconds of flight, and then approaches the optimum angle linearly until burnout, where the final angle is: $\theta_b = \frac{1}{4}\left(\frac{range}{R_{earth}}+\pi\right)$

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[30] Willam Tyrrell Thompson, *Introduction to Space Dynamics*, Dover Publications, 1986.

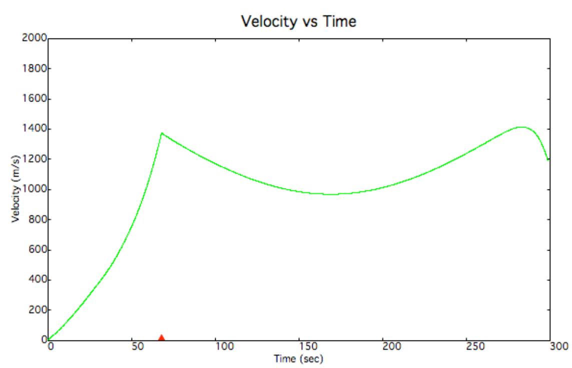
[31] Lisbeth Gronlund and David Wright, "Depressed Trajectory SLBMs: A Technical Evaluation and Arms Control Possibilities," *Science and Global Security*, 1992, Volume 3, pp 101-159.

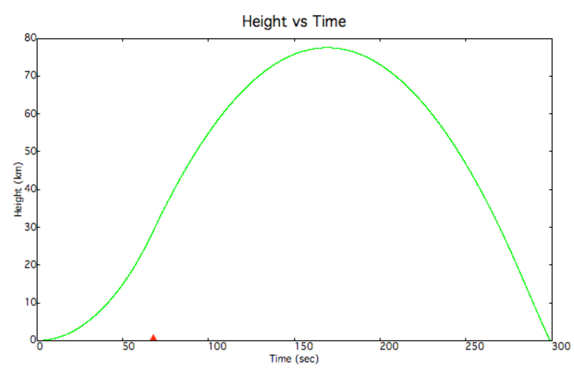
[32] Albert D. Wheelon, "Free Flight of a Ballistic Missile," Journal of the American Rocket Society, December 1959, p.915.

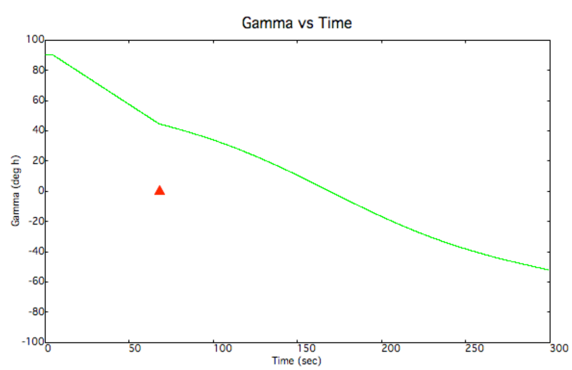
Simulation Verification

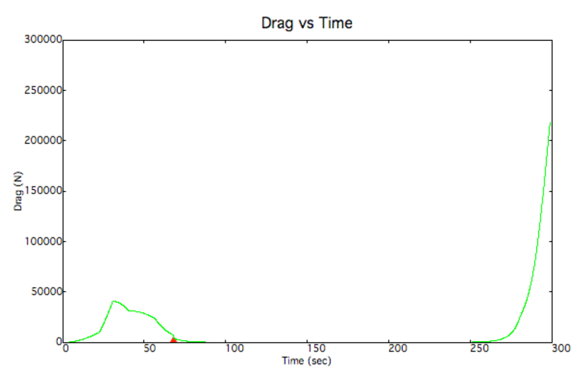
To determine the accuracy of the model, I tested the German V-2 rocket, using historical values taken from class notes[33], with the exception of an impact velocity from a more recent reference.[34] The results are all within 10% of the expected value, providing strong evidence that the model is accurate.

Result	V2 Historical	V2 Simulated	Percent Difference
Burn time [sec]	65	68.10	4.66
Burnout Altitude [km]	30	29.13	2.94
Apogee Height [km]	80	77.53	3.14
Impact Velocity [m/s]	1100	1183	7.27
Range [km]	240	238	0.84









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[33] Gregory Kennedy, *Vengeance Weapon 2: The V-2 Guided Missile,* The Smithsonian Institute, 1983, pp. 70-73.

[34] T.D. Dungan, *V-2: A Combat History of the First Ballistic Missile*, Westholme Publishing, 2005.

Results

Performing the same simulation on other vehicles yields interesting data.

Parameter	German V2	Russian R-17 / Scud	Iraq al-Hussein	DPRK Nodong	DPRK TD-1	DPRK TD -2
Source	class notes	Encyclopedia Astronautica	Encyclopedia Astronautica	Charles Vick	Charles Vick	Charles Vick
Payload [kg]	975	1,000	500	650	100 *	650
Diameter [m]	1.65	0.855	0.88	1.35	1.5	2.0
Fuel Mass [kg]	8,900	5,200	5,600	13,000	13,000 3,771 196	52,000 13,000
Dry Mass [kg]	4,000	1,150	1,200	2,300	2,400 1,100 23	3,500 2,300
Specific Impulse [sec]	210	226	226	226	226 268 280	230 264
Thrust [kg f]	27,461	8,300	9,177	30,400	30,400 6,000 2,000	105,000 31,200
Structural Mass Fraction	31%	18%	14%	15%	15.5% 23% 10.5%	6.3% 15%
Estimated Range [km]	240	300	600	1,500	2,000 - 4,000	6,400 - 15,000
Simulated Range [km]	239	297	547	1,072	1,927	5,689

* - This is the estimated mass of the satellite launched on 8/31/98. The third stage failed, resulting in the impact of the second stage shroud 1,300 km and the destroyed payload ~3,000 km downrange.[35] The mass of a real warhead is likely to be 650 kg, limiting the range to 1,275 km.

[35] Charles Vick, "Taepodong-1 Flight Chart," 1998. http://www.globalsecurity.org/wmd/world/dprk/images/td-1-flightchart-s.jpg

The results are generally accurate for short range missiles, with decreasing reliability for the longer range North Korean designs. There are several explanations for this phenomenon. First, the drag equation may no longer be accurate for long ranges, differing body types, or higher thrusts. This is certainly possible, but the time spent in the atmosphere for long range missiles is minimal compared to the entire flight time. Running the simulation without drag results in only slightly higher ranges for the Nodong and Taepodong missiles. The drag expression is probably not at fault here.

Another explanation is that the parameters provided by Charles Vick are incorrect. His numbers are derived from "circumstantial evidence, informed speculation and reverse engineering analysis"[36], probably the only sources for this sort of technical information about foreign missile capability. Most of the figures check out when compared with other open literature. The only number I truly question is the structural mass fraction on the first stage of the Taepodong-2, which is far lower than demonstrated North Korean technology. Even American and Russian designs typically operate with a structural mass fraction around 10%; 6% is far too low. However, this only contributes to a reduced range for this vehicle, and doesn't answer the question at hand.

The most likely explanation is that the high estimated missile ranges are not achievable given the current level of North Korean technology. There have been no successful missile tests to anything like the claimed ranges, and two highly publicized failures. The higher estimated ranges are numbers pushed by non-experts, with little technical backing. A more sober technical analysis shows that, unless North Korean

[36] Charles Vick, "The Closely Related Collaborative Iranian, North Korean & Pakistani Strategic Space, Ballistic Missile and Nuclear Weapon Programs", GlobalSecurity.org, May 23, 2006. http://www.globalsecurity.org/wmd/world/iran/missile-development.htm

scientists dramatically improve their nozzle designs and structural mass fraction, they will not be able to hit the United States for a very long time.

Another relevant issue is warhead design. Even if the Taepodong-2 could achieve a 7,500 km range, it can do so only with zero payload, and at a laughable accuracy. There is no evidence that North Korea has a viable nuclear warhead ready to mount on a missile, or that it would be light enough for the range to be significant. In 2005 the U.S. government stated that there was no evidence that North Korea had the capability to deliver nuclear warheads to the United States.[37] Despite speculation on high explosive testing for plutonium implosion triggers,[38] Pakistani technical assistance has focussed on heavier uranium weapons,[39] which would be more difficult to deliver by missile.

With this technical assessment as a basis, I will discuss the political repercussions of this collaborative missile program among the “Axis of Evil.”

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[37] Thomas Fingar, Assistant Secretary of State for Intelligence and Research, Statement to Senate Select Committee on Intelligence, February 16, 2005.

[38] David Sanger, “CIA Said to Find Nuclear Advances by North Koreans,” *New York Times*, July 1, 2003.

[39] Seymour Hersh, “The Cold Test,” *The New Yorker*, January 27, 2003.

Policy Implications

With two failed tests of their long-range designs, the North Korean missile program is not as enticing to potential buyers as it once was. However, even if the missiles for sale cannot yet reliably reach the United States, they still put the neighbors of all potential buyers in range. The 1,000 km provided by the proven Nodong is enough for Iran to strike Israel, Saudi Arabia and much of Turkey. It puts most of India within range of Pakistan, as well as Western China. Even tiny Yemen, which was the recipient of an intercepted shipment from North Korea in 2002,[40] could hit the populated parts of Saudi Arabia and southern Egypt. Additionally, the length of the Nodong is just inside the dimensions of a standard cargo container, opening the possibility of bringing it within range of Western powers aboard a ship.[41]

However, ballistic missiles are probably the single worst weapon to use against the United States. This is not because the national missile defense system is impenetrable; far from it. Rather, it is good old fashioned nuclear deterrence that keeps enemies at bay. Any country foolish enough to launch a missile at the United States would soon be discovered by omnipresent satellites, and quickly overwhelmed by a devastating American retaliatory strike.

In reality, the most likely use of these weapons is for domestic political purposes among suppliers and purchasers, as well as a means to project power beyond national borders. Ballistic missiles are significantly cheaper than a modern navy, and targeting foreign capitals is a large ego-booster for small powers.

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[40] PBS Newshour with Jim Lehrer, "Dangerous Cargo," December 11, 2002, http://www.pbs.org/newshour/bb/middle_east/july-dec02/yemen_12-11.html.

[41] Charles Vick, "Nodong-B," GlobalSecurity.org, March 25, 2006, http://www.globalsecurity.org/wmd/world/dprk/nd-b.htm.

Conclusion

The United States has invested hundreds of billions of dollars in a missile defense system that has yet to conduct an end-to-end integrated test, and is designed to counter a threat that has been greatly exaggerated. While the Commission to Assess the Ballistic Missile Threat to the United States, chaired by (soon to be former) Secretary of Defense Donald Rumsfeld, warned of an "imminent strategic threat," a sober technical analysis does not prove that threat to exist. Yes, North Korea has built and sold ballistic missiles. But the tests of their long range designs have failed, and they have little to no native design capability. Even if future tests are successful, their ranges are limited to perhaps 5,000 km with a current warhead, not the 15,000 km claimed by some analysts. While other states can purchase North Korean technology, they are not capable of significantly improving upon it. Additionally, the United States maintains an unmatched deterrent capability, enough to discourage any rational rogue actor.

The real threat posed by ballistic missile proliferation is to regional stability. Introducing long range missiles and nuclear warheads into inflamed regions such as the Middle East, the Indian subcontinent, and East Asia, opens the possibility for accidental launch and rapid escalation. While the United States and the Soviet Union stared each other down at the nuclear threshold for decades, other adversaries may not have as advanced a military decision process, or the experience of living with the threat of total annihilation. The future of missile proliferation looks bleak, with the impending disintegration of the NPT and the circumvention of the MTCR. On the other hand, the foreign market for budding missile designers appears to be booming. Perhaps there are job offers waiting for this graduating senior in Pyongyang, Tehran or Islamabad.

Appendix - Source Code

The following is the Python source code for the numerical integration performed in my analysis. A complete package with user interface, is available upon request.

```
def integrate(self,trajectory):
    t = 0.0# time
    v = 0               # initial v
    h = 0.001           # initial h must be small but non-zero
    psi = 0             # range angle: range = psi * Rearth
    rho = 0.0           # air density at current altitude
    p_height = 0.0 # air pressure at current altitude
    gamma = self.to_radians(90) #launch angle, from horizontal


    ##### SET INTEGRATION PARAMETERS
    tEND = 20000                #timeout value
    dtprint = 1                 #time interval between printing output
    Htrans = 20000              #height [m] at which transition from laminar to turbulent heating occurs
    deltaend = .1               #time increment used for integration
    deltatinit = .01            #time increment for t < tinit + 1 sec
    mtot = 0.0
    burntimetot = 0.0
    tinit = burntimetot + 1     # integrate more carefully during burn
    #####
    apogee = 0.0
    Thrust = 0.0
    drag = 0.0
    ##### SET CONSTANTS
    Rearth = 6370000 #[m]
    g0 = 9.8066 #[m/s^2]
    #
    ##### INITIALIZE ROCKET MODEL

    for i in range(1,self.numstages+1):
        mtot += self.m0[i] #sum total mass
        self.burntime.append(self.Isp0[i]*9.81*self.fuelmass[i]/self.thrust0[i])
        burntimetot += self.burntime[i] #sum total burn time
    mtot += self.payload

    area_missile = (self.missilediam/2)**2 * pi #[m^2]
    area_rv = self.rvdiam/2**2 * pi #[m^2]
    #####

    ##### INTEGRATE
    #
    #Initialize variables
    deltat = deltatinit
    flagdeltat = True
    m = mtot
    #
    dMdt0 = self.dMdt[1]
    tprint = dtprint #tprint is time at which printing of output will next occur
    flag = True         # controls printing parameters at burnout of stages
```

```
tlimit = self.burntime[1] # ditto
nstage = 1        # used at burnout of stages
gamma_half = gamma # angle of missile or RV w/ local horizon

#set burnout angle to optimum for MET
#uses Wheelon's form of the equations
opt_burnout_angle = pi/2 - .25*(self.est_range/Rearth + pi)
#use this optimum burnout angle to linearize turn angle, from horizontal


#Integrate
while t < tEND and h > 0: # big loop
    #save data to Results dict
    self.data['Time'].append(t) #in tenths seconds
    self.data['Height'].append(h) #in meters
    self.data['Mass'].append(m) #in kg
    self.data['Velocity'].append(v) #in meters/second
    self.data['Thrust'].append(Thrust) #in in kgf
    self.data['Drag'].append(drag) #in N
    self.data['Gamma'].append(gamma) #in degrees from horizontal
    self.data['Range'].append(Rearth*psi) #in meters

    if (t + deltat/5) >= tinit and flagdeltat == True:
        deltat = deltaend
        flagdeltat = False

    #
    # save old values
    psi_old = psi
    h_old = h
    gamma_old = gamma
    v_old = v
    m_old = m
    t_old = t
    #
    if (t + deltat/5) <= burntimetot:
        m_half = m_old - (dMdt0 * deltat/2) #burn fuel
        area = area_missile
    else:
        area = area_rv
    #calculate drag
    rho = self.density(h)
    cd = self.Cdrag(v_old,h)
    drag = cd*area*rho*(v_old**2)/2

    # calculate thrust as function of altitude
    #NEW EQUATIONS, from Charles Vick
    h_vacuum = 160934 #~100 miles
    Thrust_ideal = self.Isp0[nstage]*self.dMdt[nstage]*9.81
    if (t + deltat/5) > burntimetot:
        Thrust_pct_increase = 0
        #out of fuel, no thrust
    elif h < h_vacuum:
        h_norm = h / h_vacuum
        Thrust_pct_increase = -.4339*(h_norm)**3+.6233*(h_norm)**2-.01*(h_norm)+1.004
        #3rd order polynomial line fit from Saturn-V data on thrust vs. height

    elif h > h_vacuum and nstage == 1:
```

```
    Thrust_pct_increase = 1.19
    Thrust = Thrust_ideal*Thrust_pct_increase
elif nstage > 1:
    Thrust_pct_increase = 1
    #assuming that stage Isp is correct for vacuum
Thrust = Thrust_ideal*Thrust_pct_increase
Force = Thrust - drag
#note that Force will be negative during reentry

#OLD EQUATIONS, from David Wright
#requires us to know nozzle area, which we don't
#p0 = self.pressure(0)
#p_height = self.pressure(h)
#self.nozarea = .3 #[m^2] for TD-1
#if (t + deltat/5) > burntimetot:
#    Thrust = 0.0
#elif nstage == 1:
#    Thrust = self.Isp0[1]*self.dMdt[1]*9.81 + self.nozarea*(p0-p_height)
#elif nstage > 1:
#    Thrust = self.Isp0[nstage]*self.dMdt[nstage]*9.81


#
g = g0*Rearth**2/(h+Rearth)**2 #calculate grav accel at height

#
# Integration is variant of Runge-Kutta-2.
# 1- Calculate values at midpoint, t = t_old + deltat/2
#
t_half = t_old + deltat/2
d_psi = (v_old * cos(gamma_old)/(Rearth + h_old)) * deltat/2
psi_half = psi_old + d_psi
h_half = h_old + v_old*sin(gamma_old)*deltat/2
#
# calculate gamma

vertical_flight_period = 5
if t < vertical_flight_period:
    #force gamma to be constant early in flight
    dgamma = 0.0
elif (t >= vertical_flight_period) and (t <= burntimetot):
    dgamma = ((opt_burnout_angle - pi/2)/(burntimetot - vertical_flight_period))
else:
    dgamma = d_psi/(deltat/2) + Force/(v_old * m_old) - (g*cos(gamma_old)/v_old)

#integrate it
gamma_half = gamma_old + dgamma*deltat/2

# calculate dv
dv = (Force/m_old) - g*sin(gamma_old)

v_half = v_old + dv*deltat/2
#
#
# 2- Use derivatives at midpoint to calculate values at t + deltat
# Increment time
t += deltat
#
```

```
            d_psi_half = (v_half*cos(gamma_half))/(Rearth+h_half) * deltat
            psi = psi_old + d_psi_half
            h = h_old + v_half*sin(gamma_half)*deltat
            if h > h_old:
                apogee = h
                v_apogee = v

            vertical_flight_period = 5
            if t <= vertical_flight_period:
                dgamma_half = 0.0
            elif (t > vertical_flight_period) and (t <= burntimetot):
                dgamma_half = ((opt_burnout_angle - pi/2)/(burntimetot - vertical_flight_period))
            else:
                #use Wright's equation, hopefully not too disjoint with previous
                dgamma_half = d_psi_half/(deltat) + (Force/(v_half*m_half))- (g*cos(gamma_half)/v_half)

            gamma = gamma_old + dgamma_half*deltat

            if (t + deltat/5) <= burntimetot:
                m = m_old - dMdt0 * deltat
                #burn fuel mass

            dv_half = (Force/m_half) - g*sin(gamma_half)
            v = v_old + dv_half*deltat

            #Print data at stage burnout
            if (t + deltat / 5) > tlimit and flag == True:
                m = mtot - self.m0[nstage]
                if nstage < self.numstages:
                    nstage += 1
                    tlimit += self.burntime[nstage] #set time to next print burnout
                    dMdt0 = self.dMdt[nstage]
                else:
                    flag = False

            #END BIG LOOP

        if t >= tEND:
            #print final results
            print "Range (km): ",psi*Rearth/1000
            print "Apogee (km): ",apogee/1000
            print "Time to target (sec): ",t
        return (self.data)

    def density(self,h):
        "Calculates air density at altitude"
        rho0 = 1.225 #[kg/m^3] air density at sea level
        if h < 19200:
            #use barometric formula, where 8420 is effective height of atmosphere [m]
            rho = rho0 * exp(-h/8420)
        elif h > 19200 and h < 47000:
            #use 1976 Standard Atmosphere model
            #http://modelweb.gsfc.nasa.gov/atmos/us_standard.html
            #from http://scipp.ucsc.edu/outreach/balloon/glost/environment3.html
            rho = rho0 * (.857003 + h/57947)**-13.201
        else:
            #vacuum
            rho = 0.0
```

```
    return rho

def temperature(self,h):
    "Calculates air temperature [Celsius] at altitude [m]"
    #from equations at
    #       http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmet.html
    if h <= 11000:
        #troposphere
        t = 15.04 - .00649*h
    elif h <= 25000:
        #lower stratosphere
        t = -56.46
    elif h > 25000:
        t = -131.21 + .00299*h
    return t

def pressure(self,h):
    "Calculates air pressure [Pa] at altitude [m]"
    #from equations at
    #       http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmet.html

    t = self.temperature(h)

    if h <= 11000:
        #troposphere
        p = 101.29 * ((t+273.1)/288.08)**5.256
    elif h <= 25000:
        #lower stratosphere
        p = 22.65*exp(1.73-.000157*h)
    elif h > 25000:
        p = 2.488 * ((t+273.1)/288.08)**-11.388
    return p

def Cdrag (self,v,h):
    t = self.temperature(h) + 273.15 #convert to kelvin
    a = sqrt(1.4*287*t)
    mach = v/a

    #Drag function for V2
    #derived from Sutton, "Rocket Propulsion Elements", 7th ed, p108
    #probably not that relevant to other body types
    if mach > 5:
        cd = 0.15
    elif mach > 1.8 and mach <= 5:
        cd = -0.03125*mach + 0.30625
    elif mach > 1.2 and mach <= 1.8:
        cd = -0.25*mach + 0.7
    elif mach > 0.8 and mach <= 1.2:
        cd = 0.625*mach - 0.35
    elif mach <= 0.8:
        cd = 0.15

    #use nose cone formula
    #theta = self.to_radians(15)
    #cd = 2*sin(theta)**2

    return cd
```

```
def to_radians(self,degree):
    return degree * pi/180


if __name__ == "__main__":
        print "the simulation object"
        print "using simple text interface, minimum energy trajectory"
        print ""
        sim = Simulation(None) #this simulation object has no parent
        sim.numstages = int(raw_input("Number of stages: "))
        for i in range(1,sim.numstages+1):
                sim.fuelmass.append(float(raw_input("Fuel mass: ")))
                drymass = (float(raw_input("Dry mass: ")))
                sim.m0.append(drymass + sim.fuelmass[i])
                sim.fuelfraction.append(sim.fuelmass[i]/sim.m0[i])
                sim.Isp0.append(float(raw_input("Isp: ")))
                sim.thrust0.append(float(raw_input("Thrust (kg f): "))*9.81)
                sim.dMdt.append(float(sim.thrust0[i]/(sim.Isp0[i]*9.81)))
                sim.burntime.append(float(raw_input("Burntime (sec): ")))
        sim.payload = float(raw_input("Payload (kg): "))
        sim.maxdiam = float(raw_input("Diameter (m): "))
        sim.est_range = float(raw_input("Est range (km): "))*1000

        print '\n'
        sim.trajectory = "Minimum Energy"
        results = sim.integrate(sim.trajectory)
        print '\n'

        path = 'data.txt'
        outfile = open(path,'w')
        for i in range(1,sim.numstages+1):
                        outfile.write("STAGE %i Parameters:\n" % i)
                        outfile.write("Fuel mass (kg): " + str(sim.fuelmass[i]) + '\n')
                        outfile.write("Dry mass (kg): " + str(sim.m0[i] - sim.fuelmass[i]) + '\n')
                        outfile.write("Fuel fract: " + str(sim.fuelfraction[i]) + '\n')
                        outfile.write("Isp @ SL: " + str(sim.Isp0[i]) + '\n')
                        outfile.write("Burn time (sec): " + str(sim.burntime[i]) + '\n')
                        outfile.write("Thrust (N): " + str(sim.thrust0[i]) + '\n')
                        outfile.write("dM/dt: " + str(sim.dMdt[i]) + '\n')

        outfile.write("\nTIME,HEIGHT,VELOCITY,MASS,THRUST,DRAG,GAMMA,RANGE\n")
        flat = zip(results['Time'],
                                results['Height'],
                                results['Velocity'],
                                results['Mass'],
                                results['Thrust'],
                                results['Drag'],
                                results['Gamma'],
                                results['Range'])
        for i in range(1,len(flat)):
                        for n in range(0,len(flat[i])):
                                outfile.write('%.3f' % flat[i][n])
                                outfile.write(',')
                        outfile.write('\n')
        print "Data written to '%s'" % path
        outfile.close()
```