Start with some fundamental facts:

Radius of Earth, $R_e \approx 6400$ km

Atmosphere is approximately exponentially distributed

$H$ = scale height; $h$ = altitude; $H$  

$\rho = \rho_o e^{-h/H}$

“Sensible” atmosphere i.e. atmosphere where drag is large and there is lift, $h < 60$ km

Altitude at which it is hard to maintain in orbit 100 km

Orbital Velocity i.e. velocity at which gravitational and centripetal forces balance (close to Earth)  

$8$ km/sec

Any rocket with less than this velocity must eventually come to Earth somewhere.

GEO = orbit at which orbital velocity = rotation velocity of Earth $= 7R_e$

Satellite @ GEO over equator is stationary with respect to Earth
Notional trajectory of a ballistic missile (staged)

- First stage burnout
- Second stage burnout
- Ballistic coasting
- Observable boost phase
- Midcourse
- Ballistic reentry

Altitude (km) vs. Down range (km)

~5km/sec

NMD
Science, Technology and Policy

typical burntime ~ 200 - 300 seconds; typical impact ~20 - 30 mins

typical velocity ~ 5 - 7 km/sec (for long range)

All ballistic missiles have 3 phases:

• boost phase - powered flight; plume is observable

• midcourse - warhead (+decoys) are coasting with same initial velocity above atmosphere => no atmospheric discrimination

• reentry phase - warhead (+decoys) reenter sensible atmosphere and drag + reentry plume distinguishes between objects
Powered Flight Profile of Titan II / SS-18 ICBM
for Standard (320 Second) and 250 Second Burn-Time Trajectories

<table>
<thead>
<tr>
<th>TIME (SEC)</th>
<th>ALT (KM)</th>
<th>RNGE (KM)</th>
<th>VEL. (KM/SEC)</th>
<th>ACC. (Gs)</th>
<th>WGHT (KG)</th>
<th>THRUST (KLBF)</th>
<th>DRAG ANGLES (DEG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.04</td>
<td>0.88</td>
<td>144810.9</td>
<td>600.1</td>
<td>0.4</td>
</tr>
<tr>
<td>100</td>
<td>330.7</td>
<td>575.8</td>
<td>6.70</td>
<td>7.58</td>
<td>7377.3</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>200</td>
<td>247.5</td>
<td>394.5</td>
<td>4.90</td>
<td>3.75</td>
<td>14200.7</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>250</td>
<td>218.0</td>
<td>331.4</td>
<td>4.40</td>
<td>3.05</td>
<td>17125.1</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>170</td>
<td>164.7</td>
<td>223.6</td>
<td>3.65</td>
<td>2.21</td>
<td>22973.8</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>165</td>
<td>156.4</td>
<td>207.6</td>
<td>3.55</td>
<td>2.11</td>
<td>23948.6</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>160</td>
<td>148.1</td>
<td>192.2</td>
<td>3.45</td>
<td>2.02</td>
<td>24923.3</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>155</td>
<td>139.9</td>
<td>177.2</td>
<td>3.36</td>
<td>1.94</td>
<td>25898.1</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>150</td>
<td>131.8</td>
<td>162.7</td>
<td>3.28</td>
<td>1.87</td>
<td>26872.9</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>145</td>
<td>123.7</td>
<td>148.7</td>
<td>3.19</td>
<td>1.80</td>
<td>27847.7</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>140</td>
<td>115.7</td>
<td>135.1</td>
<td>3.11</td>
<td>1.73</td>
<td>28822.5</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>135</td>
<td>107.8</td>
<td>122.0</td>
<td>3.04</td>
<td>1.67</td>
<td>29797.2</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>130</td>
<td>99.8</td>
<td>109.2</td>
<td>2.97</td>
<td>1.62</td>
<td>30772.0</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>125</td>
<td>91.9</td>
<td>96.8</td>
<td>2.90</td>
<td>1.57</td>
<td>31746.8</td>
<td>132.1</td>
<td>0.0</td>
</tr>
<tr>
<td>115</td>
<td>76.1</td>
<td>73.3</td>
<td>2.77</td>
<td>6.49</td>
<td>38780.9</td>
<td>600.1</td>
<td>0.1</td>
</tr>
<tr>
<td>105</td>
<td>61.6</td>
<td>53.0</td>
<td>2.22</td>
<td>5.12</td>
<td>48420.0</td>
<td>600.1</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>55.2</td>
<td>44.7</td>
<td>1.99</td>
<td>4.62</td>
<td>53239.5</td>
<td>600.1</td>
<td>0.4</td>
</tr>
<tr>
<td>95</td>
<td>49.2</td>
<td>37.4</td>
<td>1.78</td>
<td>4.20</td>
<td>58059.1</td>
<td>600.1</td>
<td>0.6</td>
</tr>
<tr>
<td>90</td>
<td>43.7</td>
<td>31.1</td>
<td>1.59</td>
<td>3.82</td>
<td>62878.6</td>
<td>600.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Stage 2 Burn Completed

Stage 1 Burn Completed

**Shroud Jettisoned**

10/17/01
Boost-Phase, Mid-Course and Reentry Phases of Ballistic Missile Flight

Location of Objects Shown Every 20 Seconds

\( \theta = 22.55 \text{ degrees} \)

\( V = 7.177, 7.1935, \text{ and } 7.21 \text{ km/s} \)

<table>
<thead>
<tr>
<th>Range (Kilometers)</th>
<th>Altitude (Kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>8000</td>
<td>8000</td>
</tr>
<tr>
<td>9000</td>
<td>9000</td>
</tr>
<tr>
<td>10000</td>
<td>10000</td>
</tr>
</tbody>
</table>

Altitudes Where Reentry Effects May Be Observable (60 to 90 seconds)

Altitudes Where ICBM is in Powered Flight (200 to 300 seconds)

Ground Trace of North Korean ICBM for Attacks on Moscow, Washington, Chicago, San Francisco and Honolulu
Ground Trace of North Korean ICBM for Attacks on Moscow, Washington, Chicago, San Francisco and Honolulu

North Korean Launch Site: 39.6N, 127.3E
Chicago: 41.85N, 87.65W
San Francisco: 37.75N, 122.45W
Washington, DC: 38.9N, 77.0W
Honolulu, HI: 21.3N, 157.9W

North Korean Launch Site to Chicago = 5244.69 nmi, 10,524.02 km
Minimum Energy Loft Angle = 21.37 degrees
Velocity at Ground = 7.28 km/sec
Range Angle = 94.52 degrees
Time of Flight = 33.22 minutes

Typical missile in flight

- warhead(s) or dummy
- second stage (solid or liquid)
- first stage (solid or liquid)
- bright plume (powered)
Consider first a "simple" ballistic missile with a single warhead, no dummy or countermeasures and no ability to maneuver after burnout.

3 regions to strike missile:

- Boost phase = 200 - 300 seconds
- Midcourse = 10s of minutes
- Reentry = 60 - 90 seconds
Boost phase

Big advantages:

- Missile is easy to see (from warning satellites @ GEO) since plume is so bright in IR. Also has a large radar cross section making use of a wide range of existing radars if they are in the area.
- Only need to hit boosting missile anywhere for it to fail. If an interception is used, then almost 100 times less demanding than hitting a small warhead.
- Target destruction is immediately observable on sensors (IR or radar)
- Destroyed missile may fall back on launching state so deterring them
- Robust against simple technical countermeasures

Big disadvantages:

- Short timelines ⇒ need to act quickly
- If interceptors used, then they need to be relatively close.
- If speed of light weapons used, then space based ones need global proliferation
- Missiles short falling may fall on friendly countries
- Only get one chance to hit missile (unless launching state uses barrage firing)
Ground based interceptors used for boost phase

Note typical distances ~

700 km

* If warhead is not destroyed but keeps going ballistically, then there is a range shortfall.

• This may be a policy problem.

• Biggest policy problem

• Country like Iran requires putting ground-based interceptors in neutral or possibly unfriendly countries (due to short timelines)
First-Stage Trident II-Based Interceptor Timelines Against Powered Flight Profiles of 250 and 320 Second Burn-Time ICBMs

- 250 seconds after launch
- 50 seconds after launch
- 100 seconds after launch
- 200 seconds after launch
- 150 seconds after launch
- 50 seconds after launch
- End of Powered Flight
- 64 seconds after launch

North Korean 250 Second Burn Time ICBM
65 Second Burn-Time Trident II First-Stage Interceptor (6.1-6.3 km/sec Burnout Speed)

Location of Interceptor and ICBM Shown at 5 Second Intervals

Location of ICBM When Interceptor is Launched 95 Seconds After ICBM Liftoff
Intercept Point If Interceptor is Launched 120 Seconds After ICBM Launch

Location of THAAD-GBR Tangent to Earth
Location of Intercept Point If Interceptor is Launched 95 Seconds After ICBM Launch

Titan II / SS-18 Class Liquid Propellant ICBM

Location of ICBM When Interceptor is Launched 130 Seconds After GBI launch

Boost-Phase Kill Vehicle Capable of 10 G Maximum Divert Acceleration and 2 km/sec Total Divert Velocity

Telescope for Homing on Illuminated Targets
Neodymium YAG Laser

- Total Propellant Weight = 230 lbs
- Propellant Density = 72 lb/ft³
- Total Propellant Volume = 3.2 ft³
- Motor Weight = 80 lbs
- Thrust = 4610 lbs
- Weight of Tanks and Structure = 46 lbs
- Overall Vehicle Weight = 460 lbs
- Payload Weight = 100 lbs
- Propellant=N2O4/MMH
- Vacuum Steady State Real Engine Performance
- Specific Impulse (lbf·s/lbms) = 295
- Throat Diameter = 5.2 inches (13 meters)
- Exit Diameter = 23.2 inches (59 meters)
- Area Ratio=20
- Chamber Pressure = 125 psia
- Motor Length = 50 inches (1.27 meters)
- Chamber Diameter = 13.5 inches (35 meters)
- Spherical Fuel/Oxidizer Tank Diameters = 18 inc
- Barrel Tank
- Barrel Diameter = 10 inches (26 meters)
- Overall Length = 38.9 inches (98 meters)
- Barrel Lenght = 28.5 inches (.73 meters)
Range Shortfall of Intercepted North Korean ICBM for Various Intercept Times Prior to Burnout

5000 Kilometer Range Shortfalls

Washington

Chicago

10/17/01