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- **Basic science of ballistic missiles**
- **Basic technologies of ballistic missiles**
- **Technological uncertainties**
- **Economic uncertainties**
- **Policy uncertainties**
- **All with be discussed in this lecture**

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Start with some fundamental facts:

Radius of Earth, R_E~ 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

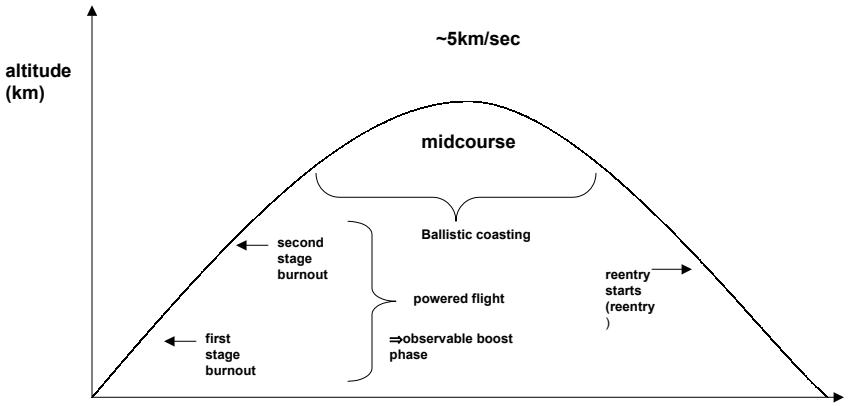
Altitude at which it is hard to maintain in orbit100 km

Orbital Velocity i e. velocity at which gravitational and centipetal 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)



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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**

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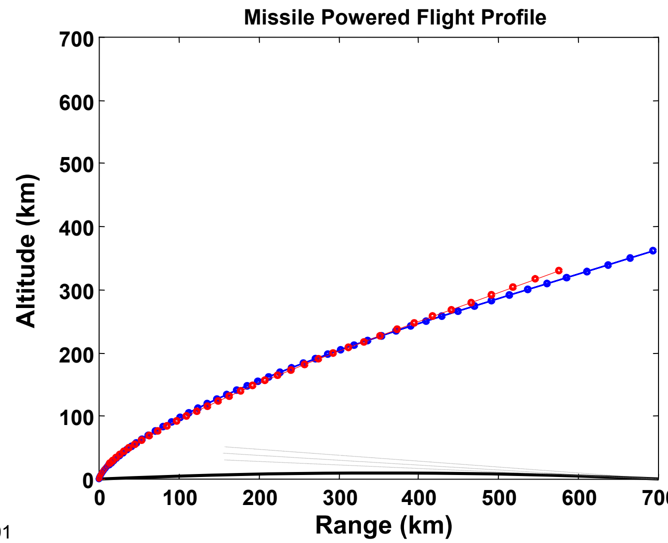
Powered Flight Profile of Titan II / SS-18 ICBM
for Standard (320 Second) and 250 Second Burn-Time Trajectories



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Powered Flight Profile of Titan II / SS-18 ICBM
for Standard (320 Second) and 250 Second Burn-Time Trajectories

Standard Titan II ICBM (320 seconds)

ModelTitan2ICBM
Baseline Titan II / SS-18 Liquid Propellant ICBM
First Stage Characteristics

Loaded Wt = 255055.000 lbs, Empty Wt = 11186.000 lbs, Specific Impulse = 283.000 sec-1
Propellant Wt = 243869.000 lbs Burn Time = 145.000

Second Stage Characteristics
Loaded Wt = 63482.000 lbs Empty Wt = 5580.000 lbs Specific Impulse = 308.000 sec-1"
Propellant Wt = 57902.000 "lbs Burn Time = 175.000

Missile Launch Gross Wt = 329187.000 lbs Missile Throw Wt = 10650.000
Missile Diameter = 9.840 feet

TIME (SEC)	ALT (KM)	RNGE (KM)	VEL. (KM/SEC)	ACC. (Gs)	WGHT (KG)	THRUST (KLBF)	DRAG (KLBF)	CD	ANGLES MOTION	(DEG) THRST
5.0	0.1	0.0	0.02	0.48	145808.1	476.0	0.1	0.200	86.899	88.000
10.0	0.2	0.0	0.05	0.53	141985.7	476.0	0.4	0.200	83.878	86.000
15.0	0.6	0.1	0.08	0.58	138163.3	476.0	1.0	0.200	81.004	84.000
20.0	1.0	0.1	0.11	0.63	134340.9	476.0	1.9	0.200	78.270	82.000
25.0	1.6	0.3	0.14	0.68	130518.5	476.0	3.0	0.200	75.668	80.000
30.0	2.3	0.5	0.17	0.74	126696.1	476.0	4.4	0.200	73.190	78.000
35.0	3.2	0.8	0.21	0.80	122873.7	476.0	5.9	0.200	70.827	76.000
40.0	4.3	1.2	0.25	0.87	119051.3	476.0	7.6	0.200	68.571	74.000
45.0	5.6	1.7	0.29	0.94	115228.9	476.0	9.1	0.200	66.415	72.000
50.0	7.0	2.4	0.34	1.01	111406.5	476.0	12.6	0.238	64.350	70.000
55.0	8.6	3.2	0.39	1.08	107584.1	476.0	15.9	0.273	62.368	68.000
60.0	10.4	4.2	0.44	1.17	103761.7	476.0	16.6	0.267	60.461	66.000
65.0	12.5	5.4	0.50	1.27	99939.3	476.0	14.8	0.260	58.626	64.000
70.0	14.7	6.8	0.56	1.38	96116.9	476.0	13.0	0.253	56.859	62.000
75.0	17.2	8.5	0.63	1.50	92294.5	476.0	10.9	0.245	55.156	60.000
80.0	19.9	10.4	0.71	1.64	88472.1	476.0	8.7	0.236	53.513	58.000
85.0	22.9	12.7	0.79	1.78	84649.7	476.0	6.6	0.226	51.925	56.000
90.0	26.1	15.3	0.87	1.93	80827.3	476.0	4.8	0.216	50.388	54.000
95.0	29.6	18.3	0.97	2.09	77004.9	476.0	3.3	0.205	48.897	52.000
100.0	33.4	21.7	1.07	2.26	73182.5	476.0	2.2	0.200	47.447	50.000
105.0	37.5	25.6	1.19	2.45	69360.1	476.0	1.5	0.200	46.034	48.000
110.0	42.0	30.0	1.31	2.66	65537.7	476.0	0.9	0.200	44.653	46.000
115.0	46.8	34.9	1.44	2.89	61715.3	476.0	0.5	0.200	43.299	44.000
120.0	51.9	40.5	1.58	3.14	57892.9	476.0	0.4	0.200	41.969	42.000
125.0	57.4	46.7	1.74	3.43	54070.5	476.0	0.2	0.200	40.658	40.000
130.0	63.2	53.8	1.91	3.76	50248.1	476.0	0.1	0.200	39.362	38.000
135.0	69.5	61.6	2.10	4.14	46425.7	476.0	0.1	0.200	38.076	36.000
140.0	76.2	70.4	2.31	4.58	42603.3	476.0	0.0	0.200	36.795	34.000
145.0	83.4	80.2	2.54	5.07	38780.9	476.0	0.0	0.200	35.623	34.000
Stage 1 Burn Completed										
150.0	90.8	90.6	2.58	1.18	32944.4	101.9	0.0	0.200	34.695	34.000
155.0	98.1	101.4	2.62	1.21	32192.4	101.9	0.0	0.200	33.795	34.000
160.0	105.3	112.4	2.67	1.23	31440.4	101.9	0.0	0.200	32.925	34.000
165.0	112.6	123.8	2.71	1.26	30688.5	101.9	0.0	0.200	32.085	34.000
170.0	119.8	135.4	2.76	1.29	29936.5	101.9	0.0	0.200	31.275	34.000
175.0	126.9	147.4	2.81	1.32	29184.5	101.9	0.0	0.200	30.496	34.000
180.0	134.0	159.7	2.87	1.35	28432.5	101.9	0.0	0.200	29.748	34.000
185.0	141.1	172.3	2.92	1.39	27680.6	101.9	0.0	0.200	29.031	34.000
190.0	148.2	185.3	2.98	1.43	26928.6	101.9	0.0	0.200	28.346	34.000
195.0	155.3	198.6	3.05	1.47	26176.6	101.9	0.0	0.200	27.693	34.000
200.0	162.4	212.3	3.11	1.51	25424.6	101.9	0.0	0.200	27.071	34.000
205.0	169.5	226.3	3.18	1.56	24672.7	101.9	0.0	0.200	26.481	34.000
210.0	176.6	240.7	3.25	1.61	23920.7	101.9	0.0	0.200	25.923	34.000
215.0	183.7	255.6	3.32	1.66	23168.7	101.9	0.0	0.200	25.396	34.000
220.0	190.8	270.8	3.40	1.72	22416.8	101.9	0.0	0.200	24.901	34.000
225.0	198.0	286.4	3.48	1.78	21664.8	101.9	0.0	0.200	24.437	34.000
230.0	205.2	302.5	3.57	1.85	20912.8	101.9	0.0	0.200	24.004	34.000
Shroud Jettisoned										
235.0	212.5	319.0	3.66	1.92	20160.8	101.9	0.0	0.200	23.603	34.000
240.0	219.9	336.0	3.75	2.00	19408.9	101.9	0.0	0.200	23.233	34.000
245.0	227.3	353.5	3.85	2.09	18656.9	101.9	0.0	0.200	22.893	34.000
250.0	234.9	371.5	3.95	2.19	17904.9	101.9	0.0	0.200	22.585	34.000
255.0	242.5	390.0	4.06	2.29	17152.9	101.9	0.0	0.200	22.308	34.000
260.0	250.3	409.1	4.17	2.41	16401.0	101.9	0.0	0.200	22.061	34.000
265.0	258.2	428.7	4.29	2.53	15649.0	101.9	0.0	0.200	21.846	34.000
270.0	266.3	449.0	4.42	2.68	14897.0	101.9	0.0	0.200	21.661	34.000
275.0	274.5	469.8	4.55	2.83	14145.0	101.9	0.0	0.200	21.508	34.000
280.0	283.0	491.4	4.70	3.01	13393.1	101.9	0.0	0.200	21.386	34.000
285.0	291.7	513.6	4.85	3.21	12641.1	101.9	0.0	0.200	21.297	34.000
290.0	300.6	536.6	5.01	3.43	11889.1	101.9	0.0	0.200	21.240	34.000
295.0	309.8	560.4	5.19	3.68	11137.1	101.9	0.0	0.200	21.216	34.000
300.0	319.4	585.0	5.37	3.98	10385.2	101.9	0.0	0.200	21.226	34.000
305.0	329.3	610.5	5.58	4.31	9633.2	101.9	0.0	0.200	21.271	34.000
310.0	339.7	637.1	5.80	4.71	8881.2	101.9	0.0	0.200	21.353	34.000
315.0	350.5	664.6	6.04	5.18	8129.2	101.9	0.0	0.200	21.474	34.000
320.0	361.8	693.4	6.31	5.75	7377.3	101.9	0.0	0.200	21.636	34.000
Stage 2 Burn Completed										

Fast-Burn Titan II ICBM (250 seconds)

ModelTitan2icbm01FastBurnb
Baseline Titan II / SS-18 Liquid Propellant ICBM
First Stage Characteristics

Loaded Wt = 255055.000 lbs, Empty Wt = 11186.000 lbs, Specific Impulse = 283.000 sec-1
Propellant Wt = 243869.000 lbs Burn Time = 115.000

Second Stage Characteristics
Loaded Wt = 63482.000 lbs Empty Wt = 5580.000 lbs Specific Impulse = 308.000 sec-1"
Propellant Wt = 57902.000 "lbs Burn Time = 135.000

Missile Launch Gross Wt = 329187.000 lbs Missile Throw Wt = 10650.000
Missile Diameter = 9.840 feet

TIME (SEC)	ALT (KM)	RNGE (KM)	VEL. (KM/SEC)	ACC. (Gs)	WGHT (KG)	THRUST (KLBF)	DRAG (KLBF)	CD	ANGLES MOTION	(DEG) THRST
5.0	0.1	0.0	0.04	0.88	144810.9	600.1	0.4	0.200	86.732	87.000
10.0	0.4	0.0	0.09	0.95	139991.4	600.1	1.4	0.200	83.543	84.000
15.0	1.0	0.1	0.14	1.03	135171.8	600.1	3.2	0.200	80.445	81.000
20.0	1.8	0.3	0.19	1.11	130352.3	600.1	5.7	0.200	77.435	78.000
25.0	2.9	0.5	0.24	1.20	125532.7	600.1	8.5	0.200	74.509	75.000
30.0	4.2	0.9	0.30	1.30	120713.2	600.1	11.5	0.200	71.663	72.000
35.0	5.8	1.5	0.37	1.39	115893.6	600.1	19.3	0.271	68.894	69.000
40.0	7.6	2.3	0.44	1.50	111074.1	600.1	22.0	0.267	66.192	66.000
45.0	9.8	3.3	0.51	1.64	106254.5	600.1	23.2	0.259	63.556	63.000
50.0	12.2	4.6	0.59	1.79	101435.0	600.1	23.1	0.249	60.984	60.000
55.0	15.0	6.2	0.68	1.98	96615.5	600.1	17.4	0.239	58.476	57.000
60.0	18.0	8.2	0.78	2.17	91795.9	600.1	13.6	0.228	56.031	54.000
65.0	21.4	10.6	0.88	2.39	86976.4	600.1	10.0	0.215	53.644	51.000
70.0	25.1	13.4	1.00	2.62	82156.8	600.1	6.8	0.201	51.313	48.000
75.0	29.2	16.9	1.13	2.87	77337.3	600.1	4.6	0.200	49.030	45.000
80.0	33.7	20.9	1.27	3.15	72517.7	600.1	3.0	0.200	46.789	42.000
85.0	38.5	25.6	1.42	3.47	67698.2	600.1	1.8	0.200	44.584	39.000
90.0	43.7	31.1	1.59	3.82	62878.6	600.1	1.0	0.200	42.407	36.000
95.0	49.2	37.4	1.78	4.20	58059.1	600.1	0.6	0.200	40.274	34.000
100.0	55.2	44.7	1.99	4.62	53239.5	600.1	0.4	0.200	38.437	34.000
105.0	61.6	53.0	2.22	5.12	48420.0	600.1	0.2	0.200	36.919	34.000
110.0	68.6	62.5	2.48	5.73	43600.5	600.1	0.1	0.200	35.671	34.000
115.0	76.1	73.3	2.77	6.49	38780.9	600.1	0.1	0.200	34.653	34.000
Stage 1 Burn Completed										
120.0	84.0	84.9	2.84	1.52	32721.6	132.1	0.0	0.200	33.818	34.000
125.0	91.9	96.8	2.90	1.57	31746.8	132.1	0.0	0.200	33.019	34.000
130.0	99.8	109.2	2.97	1.62	30772.0	132.1	0.0	0.200	32.256	34.000
135.0	107.8	122.0	3.04	1.67	29797.2	132.1	0.0	0.200	31.530	34.000
140.0	115.7	135.1	3.11	1.73	28822.5	132.1	0.0	0.200	30.840	34.000
145.0	123.7	148.7	3.19	1.80	27847.7	132.1	0.0	0.200	30.187	34.000
150.0	131.8	162.7	3.28	1.87	26872.9	132.1	0.0	0.200	29.571	34.000
155.0	139.9	177.2	3.36	1.94	25898.1	132.1	0.0	0.200	28.991	34.000
160.0	148.1	192.2	3.45	2.02	24923.3	132.1	0.0	0.200	28.447	34.000
165.0	156.4	207.6	3.55	2.11	23948.6	132.1	0.0	0.200	27.940	34.000
170.0	164.7	223.6	3.65	2.21	22973.8	132.1	0.0	0.200	27.468	34.000
175.0	173.2	240.1	3.76	2.32	21999.0	132.1	0.0	0.200	27.032	34.000
180.0	181.8	257.1	3.87	2.44	21024.2	132.1	0.0	0.200	26.631	34.000
Shroud Jettisoned										
185.0	190.6	274.7	3.99	2.57	20049.4	132.1	0.0	0.200	26.266	34.000
190.0	199.5	293.0	4.12	2.71	19074.6	132.1	0.0	0.200	25.936	34.000
195.0	208.6	311.8	4.26	2.87	18099.9	132.1	0.0	0.200	25.641	34.000
200.0	218.0	331.4	4.40	3.05	17125.1	132.1	0.0	0.200	25.382	34.000
205.0	227.5	351.6	4.56	3.26	16150.3	132.1	0.0	0.200	25.158	34.000
210.0	237.3	372.7	4.72	3.49	15175.5	132.1	0.0	0.200	24.969	34.000
215.0	247.5	394.5	4.90	3.75	14200.7	132.1	0.0	0.200	24.817	34.000
220.0	257.9	417.2	5.09	4.05	13226.0	132.1	0.0	0.200	24.701	34.000
225.0	268.8	440.8	5.30	4.41	12251.2	132.1	0.0	0.200	24.623	34.000
230.0	280.0	465.4	5.52	4.82	11276.4	132.1	0.0	0.200	24.583	34.000
235.0	291.8	491.1	5.77	5.31	10301.6	132.1	0.0	0.200	24.583	34.000
240.0	304.1	517.9	6.05	5.91	9326.8	132.1	0.0	0.200	24.625	34.000
245.0	317.0	546.1	6.35	6.65	8352.1	132.1	0.0	0.200	24.712	34.000
250.0	330.7	575.8	6.70	7.58	7377.3	132.1	0.0	0.200	24.847	34.000
Stage 2 Burn Completed										

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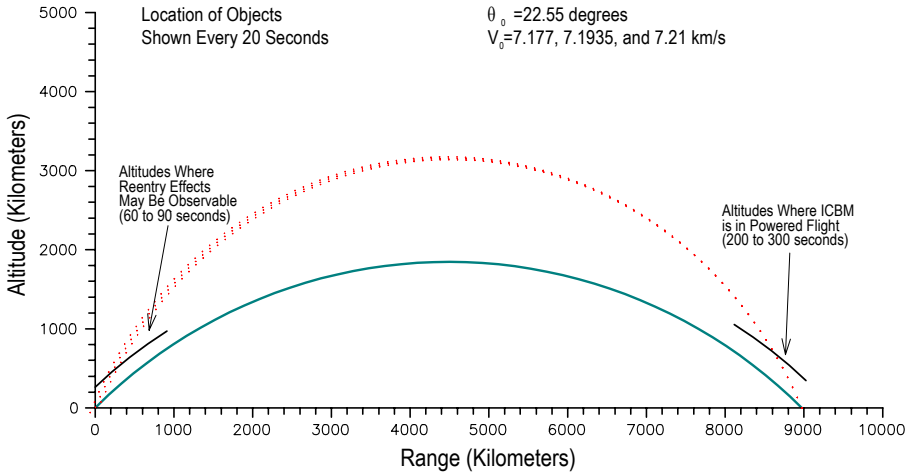
Boost-Phase, Mid-Course and Reentry Phases of Ballistic Missile Flight



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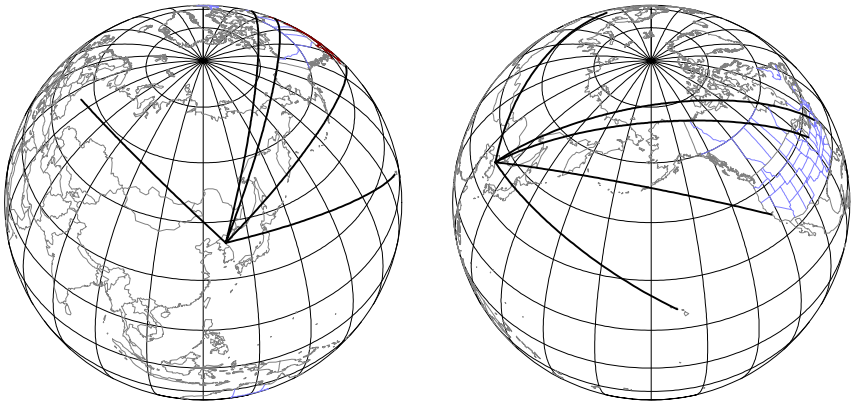
Ground Trace of North Korean ICBM for Attacks on Moscow, Washington, Chicago, San Francisco and Honolulu



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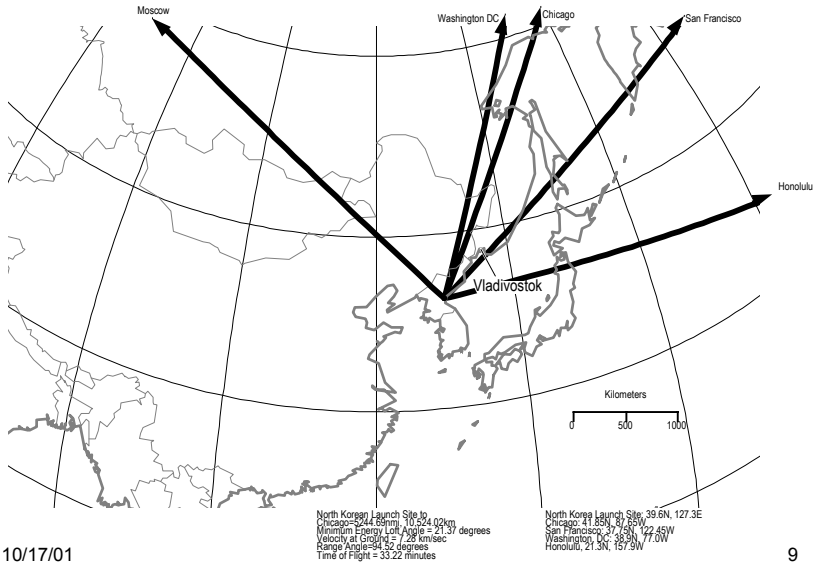
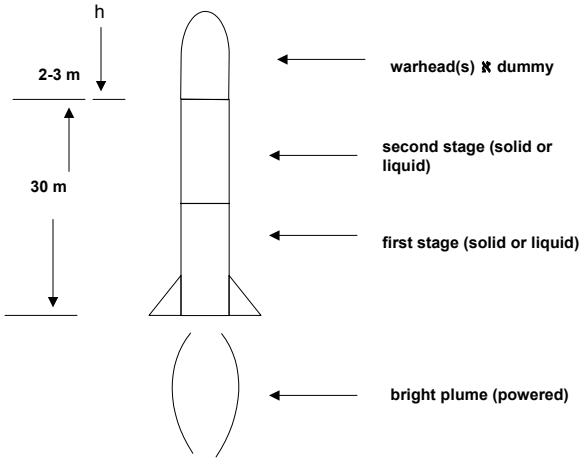
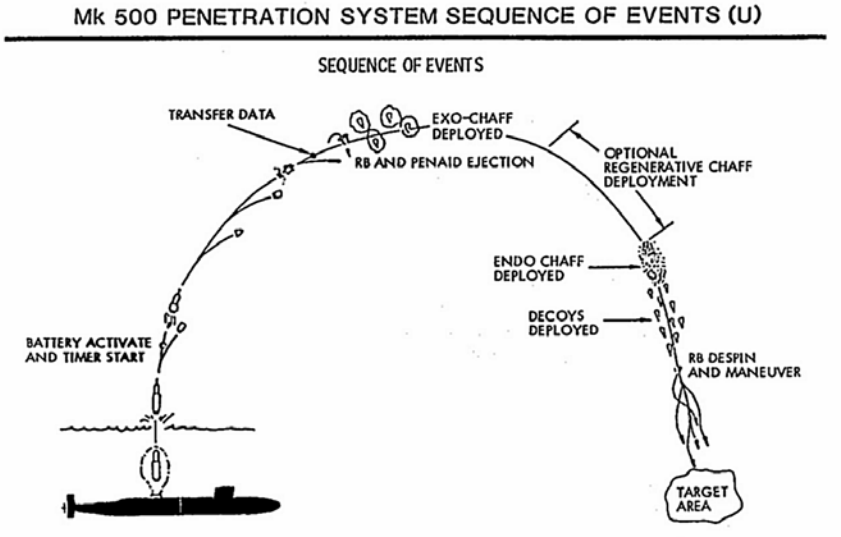
Ground Trace of North Korean ICBM for Attacks on Moscow, Washington, Chicago, San Francisco and Honolulu



Typical missile in flight



Countermeasures and National Missile Defense



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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

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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

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Boost phase

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)

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Ground based interceptors used for boost phase

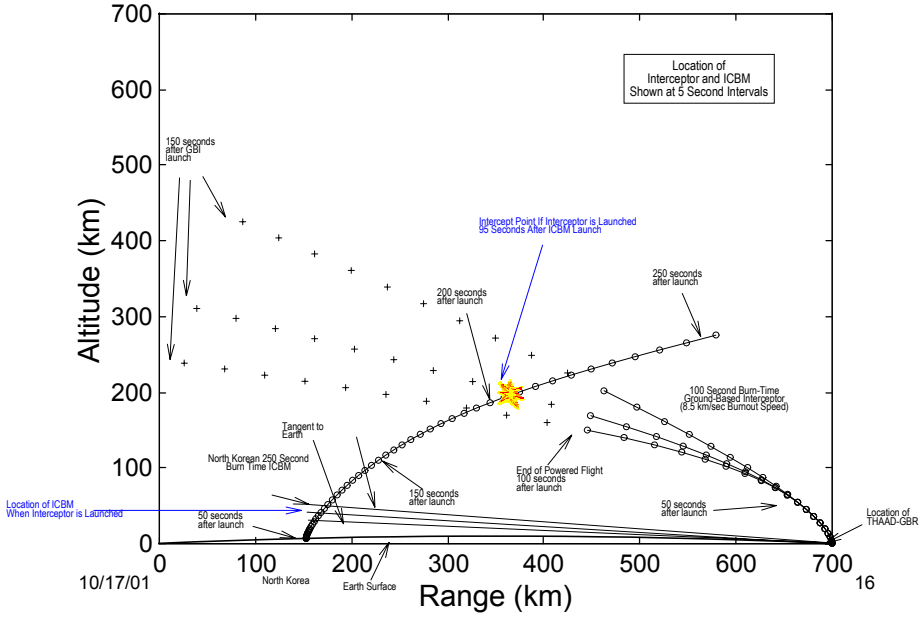
Note typical distances ~

700 km

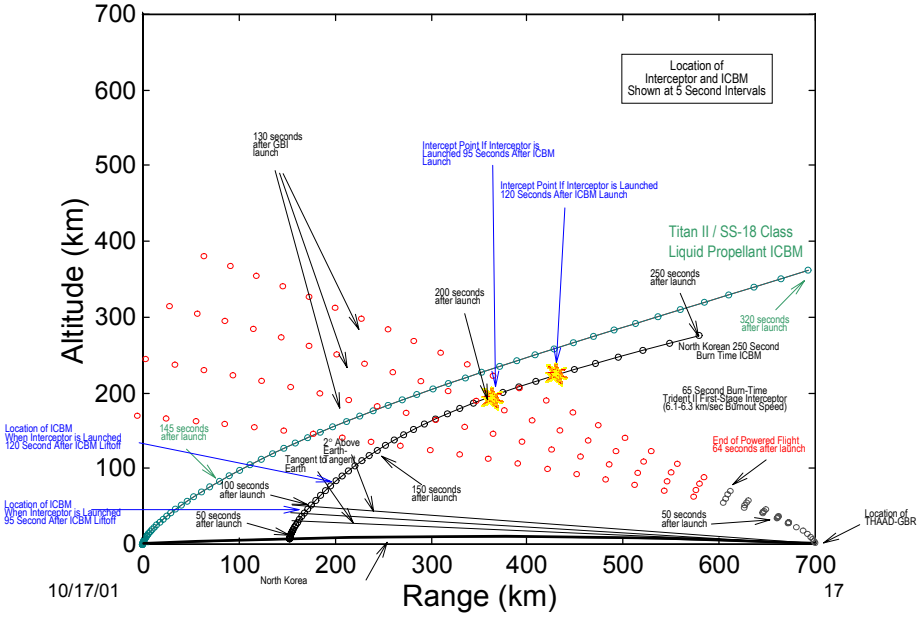
- **If warhead is not destroyed but keeps going ballistically, then there is a range shortfall.**
  - **This may be a policy problem.**

- **Biggest policy problem**
- **Country like Iran requires putting ground-based interceptors in neutral or possibly unfriendly countries (due to short timelines)**

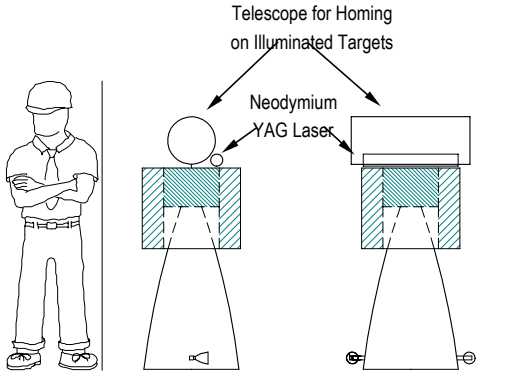
Powered Flight Profiles of *Postulated* North Korean 250 Second Burn-time ICBM and Russian-US 100 Second Burn-Time Ground-Based Interceptor



First-Stage Trident II-Based Interceptor Timelines Against Powered Flight Profiles of 250 and 320 Second Burn-Time ICBMs

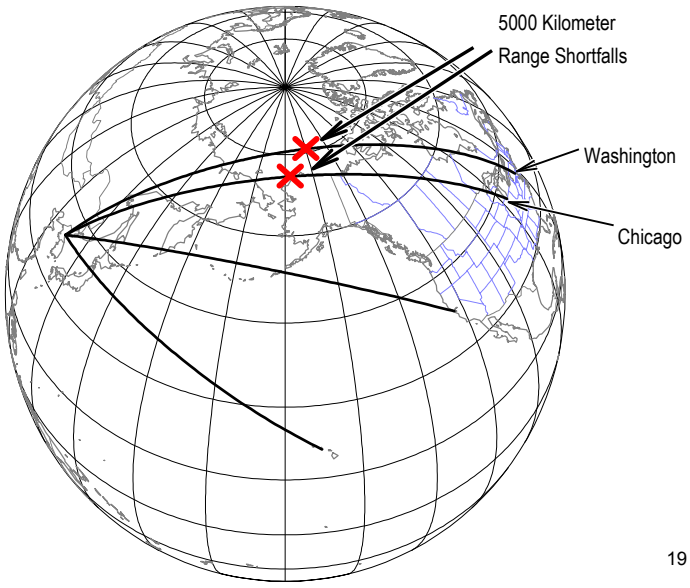


Boost-Phase Kill Vehicle Capable of 10 G Maximum Divert Acceleration and 2 km/sec Total Divert Velocity



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 = 38.5 inches (.98 meters)
Barrel Lenght = 28.5 inches (.73 meters)

Range Shortfall of Intercepted North Korean ICBM for Various Intercept Times Prior to Burnout



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