

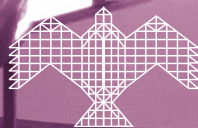
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NORTH KOREA'S SUCCESSFUL SPACE LAUNCH

April 2013

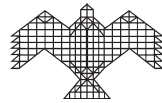


International Strategic and Security Studies Programme
NATIONAL INSTITUTE OF ADVANCED STUDIES

Bangalore, India

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**S.Chandrashekar
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SUMMARY OVERVIEW

On December 12 2012 North Korea surprised the world by successfully placing a remote sensing satellite in a sun synchronous orbit using an indigenously developed launcher called the Unha.

In accordance with international norms of behavior associated with such launches over international waters North Korea had sent a notification to the International Maritime Organization (IMO) about the launch window as well as the impact zones for the first stage, the second stage and the heat shroud.

Using publicly available information and images of the Unha launcher as well as the specific information on the first stage put out by South Korea after recovering and analyzing the debris from the first stage, the International Strategic & Security Studies Programme (ISSSP) at the National Institute of Advanced Studies (NIAS) attempted to reconstruct the trajectory of the successful launch.

From a given launch site there are in principle many trajectories that can inject a satellite into a specified orbit. If the physical dimensions of the rocket, the number of stages and the amount of fuel are known the number of possible trajectories will reduce. In addition if the impact points of the different stages of the rocket are known the number of possible trajectories can be reduced further since these impact points will determine the latitude, longitude, altitude and velocity at which the burnout of the stages will occur. Normally the

final stage of the rocket also goes into orbit. Therefore if we know the achieved orbit of the injected satellite we can also reconstruct the trajectory of the final stage.

For the December 12 2012 launch of the Unha, all this information was available or reasonable estimates could be made from images of the launcher. This enables us to reconstruct the trajectory flown by the Unha launcher with a reasonable degree of accuracy.

Through an iterative process we were able to obtain a trajectory that matches well with the midpoints of the notified impact zones as well as the achieved orbit.

Based on the results from our reconstructed trajectory we were also able to make certain inferences about North Korea's Space and Missile Capabilities.

The analysis suggests that North Korea is somewhat more advanced than either Iran or Pakistan in space and missile technologies and products. This assessment, more than the actual performance of the Unha launcher as a missile, must be a source of considerable concern to North Korea's immediate neighbours as well as the United States.

The available evidence based on the recovery of the first stage debris by South Korea indicates that the first stage of the Unha Launcher comprises a cluster of four Nodong Engines that have a common turbo pump and common tanks for the kerosene propellant and the RFNA

oxidizer. The first stage sea level specific impulse that best fits the trajectory is only 229 seconds as compared to the initial assumed value of 232 seconds. This is consistent with a Kerosene RFNA fuel and oxidizer combination typical of the original Scud A Soviet era technology that has been modified and scaled up for a space booster application. The addition of four vernier engines and their integration into a unified stage with autonomous control also represents a significant move away from the crude graphite jet vane control systems of the early Scud A technology used in the Nodong, Pakistan's Ghauri as well as Iran's Shahab 3. Though the technology is old the scaling up and improvements do indicate significant capabilities within North Korea.

The second stage of the Unha does not use a Nodong engine as assumed by most analysts. We found that the second stage vacuum specific impulse that best fits the trajectory is about 270 seconds. This is not compatible with the 250 to 255 seconds vacuum specific impulse of the Nodong that uses a kerosene RFNA fuel oxidizer combination. The thrust of the engine that powers this stage is also much lower than that of the Nodong engine suggesting that the stage and the engine are optimized for a satellite launch and not directly derived from a missile application. The second stage most probably uses a UDMH RFNA fuel and oxidizer combination that is compatible with the Scud B technology of the Soviet era.

Though it would have been easier for the North Korea to have used a regular missile engine for the Unha second stage they choose to develop an engine and stage specifically designed for a satellite mission. This indicates a substantial in-house capability that has built upon imported technology to not only improve

it but to use the knowledge acquired to scale-up, re-design, develop, test and launch a new stage.

Our Trajectory Model also suggests that the third stage uses an advanced engine with a specific impulse in the range of 288 to 290 seconds. The results also suggest that this is a light weight stage with a high propellant load factor of around 86%. The engine that powers this stage uses an advanced propellant oxidizer combination such as UDMH and Nitrogen Tetroxide. This propellant and oxidizer combination was not used in the Scud series development. North Korea's possession of this stage indicates that they have the knowledge and capabilities to indigenously design, develop, test and integrate such an advanced engine and stage into a space launcher. This is no mean achievement for a supposedly backward country like North Korea.

Apart from these hard technological achievements related to the development of the propulsion units and the stages for the Unha, the launch provides visible evidence that North Korea has been able to integrate these hard technologies with the softer technologies of mission planning and management of a complex project.

The vehicle trajectory including the maneuvers after liftoff, the pitching down of the second stage after first stage separation, maintaining control during the fairly long coast phase, the yaw maneuver of the third stage and the final injection into a fairly good sun synchronous orbit shows a strong and well-developed internal organization of effort within North Korea. The division of work and the integration of these various diverse subsystems and components into a whole launcher and the planning and execution of the launch mission

show that North Korea has made commendable progress in its mastery of missile and space launcher products and technologies.

Though the Unha has been primarily designed for a space application it can also be used as a missile.

The range of the Unha with a 1000 kg payload launched due north towards the US or Canada is 5950 Km.

A due North East launch from the Launch site with a 1000 kg payload (sufficient for a nuclear warhead) can reach most parts of Alaska.

BACKGROUND

On December 12 2012 North Korea successfully placed a 100 kg Kwanmongsong satellite into a 494km by 588 km sun synchronous orbit used by remote sensing satellites.¹

Prior to the actual launch North Korea had also sent a notification to the International Maritime Organization about the launch window and the impact zones for the first stage, the second stage as well as the heat shroud that protects the satellite during the ascent phase of the trajectory.^{2,3} These zones differed slightly from the earlier notified zones that North Korea had communicated for the third flight of the Unha launcher which failed on April 12 2012.⁴

From a given launch site there are in principle many trajectories that can inject a satellite into a specified orbit. If the physical dimensions of the rocket, the number of stages and the amount of fuel are known the number of possible trajectories will reduce. In addition if the impact points of the different stages of the rocket are known the number of possible trajectories can be reduced further since these impact points will determine the latitude, longitude, altitude and velocity at which the burnout of the stages will occur. Normally the final stage of the rocket also goes into orbit. Therefore if we know the achieved orbit of the

injected satellite we can also reconstruct the trajectory of the final stage.

For the December 12 2012 launch of the Unha, all this information was available or estimates could be made from images of the launcher. This enables us to reconstruct the trajectory flown by the Unha launcher with a reasonable degree of accuracy.

Given the location of the launch site and the splashdown zones for the spent stages of the rocket, it is clear that North Korea has successfully carried out a fairly complex yaw maneuver during the operation of the third stage of the rocket to change the inclination of the orbit from about 88 degrees to the 97.4 degree inclination needed by a 500 km sun synchronous remote sensing satellite. Though North Korea had indicated even prior to the failed April 2012 flight that they were planning a launch into a sun synchronous orbit, analysts including some in India were skeptical whether they would indeed achieve such a capability.⁵

The successful launch into a difficult-to-achieve orbit has forced analysts across the world to revise their assessments of North Korea's space and missile capabilities. The recovery of the first stage debris from the sea by South Korea and the subsequent findings that they have made public, provide additional inputs for evaluating the Unha launcher and validating its technical parameters.⁶

¹ Jonathan's Space Report, No. 671, 2012 Dec 12 Somerville, MA USA was the first report put out in the public domain based on data from NORAD

² The announcement for the April 12 2012 launch did not include a splashdown zone for the heat shroud.

³ Though this is the fifth attempt by North Korea to place a satellite in orbit it is only the fourth attempt using the Unha launcher.

⁴ David Wright, "North Korea Gives Location Of Splashdown Zones, Begins Assembling Rocket", Union of Concerned Scientists, All Things Nuclear, December 4 2012, at <http://allthingsnuclear.org/north-korea-gives-location-of-splashdown-zones-begins-assembling-rocket/>

⁵ An earlier report put out by the International Strategic and Security Studies Programme (ISSSP) of the National Institute of Advanced Studies (NIAS) assumed that it was too risky for North Korea to carry out the yaw maneuver and only analyzed a simple in plane launch that gives an orbit inclination of 88 degrees. See footnote 7.

The International Strategic and Security Studies Programme (ISSSP) at the National Institute of Advanced Studies (NIAS) which had earlier brought out a report on the earlier failed Unha 3 launch⁷ also decided to re-assess North Korea's Space and Missile capabilities in the light of this new information. This report that is based upon our earlier work will hopefully complement work that is currently going on across the world to understand the enigma that is North Korea. The technical perspective that we bring may provide some insights that could help decipher North Korea's motives and aspirations for pursuing these difficult space and missile technologies.

HIGHLIGHTS OF THE SOUTH KOREA REPORT ON THE FIRST STAGE DEBRIS OF THE UNHA LAUNCHER

As mentioned earlier after recovering the debris of the first stage South Korea has put out their evaluation of the first stage of North Korea's Unha Launcher.⁸

Their findings are briefly summarized below.

The first stage is made up of a cluster of four Nodong engines.⁹

These four engines use common tanks and turbo pumps for transferring the fuel and

oxidizer to the four separate engines.

The fuel used is kerosene.

The oxidizer used is Red Fuming Nitric Acid (RFNA).¹⁰

Four independent smaller vernier engines are used for providing pitch and yaw control for the launcher during the operation of the first stage. This is different from the jet vane control used in the typical Nodong/ Scud missile.

The diameter of the first stage is 2.4 m

The overall length of the first stage is 15 m. The length of the engine cluster is 2.7 m.

They also state that the ratio of the volume of the propellant tank to the volume of the oxidizer tank is 0.67.

The thrust of each of the Nodong engines is estimated to be 27 tonnes. The thrust of the vernier engines is put at 3 tones. Together the four Nodong engines and the four vernier engines provide a combined thrust of 120 tonnes for the first stage.¹¹

Though South Korea has recovered only the first stage of the Unha launcher they also make some inferences about the second and third stages as well as the satellite. Their estimate of the Gross mass of the Unha launcher is 90 tonnes out of which they indicate that 48 tonnes would be the oxidizer.¹² This seems to be

⁶ An English translation of South Korea's report has been put out David Wright. See "North Korean Long-range Missile Debris Survey" Ministry of Defense, (English translation by D. Wright revised 1/27/13) available at <http://www.ucsusa.org/assets/documents/nwgs/SK-report-on-NK-rocket-debris-analysis-translation-1-18-13.pdf>

⁷ S.Chandrashekar, N. Ramani, RajaramNagappa, "North Korea's Unha 3 Space Launch", International Strategic and Security Studies Programme, National Institute of Advanced Studies Report R10-2012, August 2012.

⁸ See footnote 6

⁹ The Nodong is a single stage missile scaled up and derived from Soviet Scud technology that North Korea exported to Pakistan where it is known as the Ghauri and to Iran where it is known as the Shahab 3.

¹⁰ Red Fuming Nitric Acid is a common oxidizer used in rocketry

¹¹ Our trajectory model assumes a thrust of about 128 tonnes for the first stage. From our trajectory model values of 120 tonnes thrust are not sufficient to place the satellite in orbit.

¹² The report makes it clear that these are estimated. They are not based on measurements made on recovered debris. The South Korean report of a Gross Mass of 90 tonnes appears to be on the higher side. The Gross Mass of the Vehicle that matches with the impact points and the achieved orbit is a shade under 80 tonnes.

based on the assumption that both the second as well as the third stage engines of the Unha use the same RFNA and kerosene as oxidizer and fuel respectively.¹³

Our earlier report on the failed Unha 3 launch used images of the Unha launcher to estimate the dimensions of the various stages of the missile. These dimensions were derived on the assumption that the second stage was a Nodong with a diameter of 1.35 m. This value was used to estimate the various tank lengths and diameters for the stages, the length of the engines and the length of the satellite. The tank length values were converted to propellant masses and stage masses using missile engineering expert knowledge.

This data was then used to run a trajectory model that tried to fit the impact zone data with the trajectory. Through an iterative process that also involved some additional mass to be put into the second and third stages we were able to obtain a reasonable match between the trajectory and the impact zones of the spent first and second stage.¹⁴

The availability of new information on the first stage as well as the clear evidence that North Korea had carried out a fairly sophisticated yaw maneuver during the flight of the third stage of the Unha launch to change the

plane of the orbit from about 88 degrees to the 97.4 degrees required for a sun synchronous orbit made it necessary to revisit and update our earlier findings.¹⁵

The new information on the first stage¹⁶ was used to re-estimate the propellant and stage masses for the Unha launcher. Using these estimates we then used our trajectory programme through an iterative process to fit the vehicle parameters with the known impact points of the first stage the shroud and the 2nd stage. This iterative process provides us with a baseline for looking at the performance of the third stage and working out the requirements for achieving orbit. We can then examine how North Korea may have acquired the capabilities to build such stages and the consequent implications for the future. This approach will also reveal the adequacy or the inadequacy of the assumptions we make regarding the various parameters such as propellant masses, stage masses as well as the thrusts and specific impulses of the various stages.

The detail of the iterative process that was used to match the performance of the Unha 4 with the known impact points of the spent stages and the achieved orbit is provided below.¹⁷

¹³ Since the specific impulse of the Kerosene RFNA combination is on the lower side this implies that more fuel and oxidizer may be needed for providing the required increase in velocity for reaching orbit.

¹⁴ See footnote 7 Table 4 p 17 for the launcher parameters that match the mid points of the impact zones for the first and second stages.

¹⁵ There are some major differences between our current analysis and the earlier analysis. In the earlier analysis a pitch down maneuver was carried out by the third stage after second stage burnout. This is carried out when the launcher velocity is about 4 km per sec and involves a significant penalty in terms of the delta v needed. The yaw maneuver was also not factored in since we did not expect North Korea to be able to perform such a risky maneuver. In our current version the pitch down maneuver is carried out by the second stage immediately after the first stage burnout.

¹⁶ The diameter of the second stage is about 1.4 m and that of the third stage is about 1.2 m

¹⁷ The mid points of the impact zones specified by North Korea have been used to shape the trajectory.

MATCHING TRAJECTORY AND THE EMPIRICAL DATA

The first step involved was to update the parameters of the Unha launcher based on the debris analysis put out by South Korea. Knowing that the diameter of the first stage was 2.4 m this involved updating all measurements on the image of the Unha launcher we had used in our earlier report.¹⁸ The baseline configuration that we arrived at is provided in Table 1.

The launcher has a Lift-Off Weight (LOW) of 79067 kg. The specific impulse assumed for the first stage, the second stage and the third stage were 232 seconds (Isp sea level), 255 seconds (Isp Vacuum) and 260 seconds (Isp vacuum) for the first, second and third stages respectively.²⁰ This was based on the assumption that the three stages used the same fuel and oxidizer combination of kerosene and Red Fuming Nitric Acid (RFNA).

Without worrying too much about whether the satellite would achieve orbit we ran our trajectory model to try and match the impact points of the first and second stages only.

Our experiments with different pitch angles²¹ and azimuth angles²² quickly revealed that simultaneously matching the impact points of the first and second stages with vehicle configuration parameters of Table 1 was very difficult. If the first stage impact point was

Table 1: Initial Parameters for the Unha Launcher

Parameter	Value
Stage 1 Parameters	
Propellant mass stage 1 (kg)	55287
Inert mass stage2 (kg)	10531
Stage mass (kg)	65817
Fuel fraction	0.84
Thrust Sea level (Newtons) ¹⁹	1318598
Isp Sea Level (seconds)	232
Burn time computed (seconds)	95.33
Area of cross section (m ²)	4.52
Stage 2 Parameters	
Propellant mass stage 2 (kg)	8755
Inert mass stage 2 (kg)	2327
Stage mass (kg)	11083
Fuel fraction	0.79
Thrust (Newtons)	210000
Isp vacuum(seconds)	255
Burn time computed (seconds)	104.29
Area of cross section (m ²)	1.52
Stage 3 Parameters	
Propellant mass stage 3 (kg)	1449
Inert mass stage 3 (kg)	318
Stage mass (kg)	1767
Fuel fraction	0.82
Thrust (Newtons)	93000
Isp vacuum(seconds)	260
Burn time computed (seconds)	40
Area of cross section(m ²)	1.02
Satellite mass (kg)	100
Shroud mass (kg)	300
Lift off weight (kg)	79067

matched the second stage reached a very high altitude making the second stage fall far short of

¹⁸ See footnote 7. Our earlier assessment was based on the assumption that the second stage was a Nodong derivative with a diameter of 1.35 m

¹⁹ For a booster stage it is more appropriate to use the sea level thrust and Isp values. Based on empirical data typical variation of thrust with altitude has been modeled and incorporated into our trajectory software. A 10% variation in thrust and a similar variation in Isp values seem appropriate based on a sample of values estimated from typical booster stages. For the upper stages it is more appropriate to use vacuum values of thrust as well as Isp.

²⁰ This assumption assumes that the second stage as well as the third stage use RFNA and Kerosene as oxidizer and fuel respectively.

²¹ A vertical trajectory – straight up from the launch pad has a pitch angle as per our convention of 90 degrees.

²² A due north launch from the launch site has an azimuth of zero degree. Azimuth can change from zero to 360 degrees.

its actual impact location. Matching the impact point of the second stage with such a trajectory called for a major pitch down maneuver of the second stage that would consume a lot of the propellant of the second stage.²³ Given the physical constraints of first and second stage sizes these did not appear feasible trajectories to pursue.

One way to reduce the altitude that the second stage could reach (an altitude at the end of the coasting of the third stage close to 500 km is needed) is to increase the weight of the second stage. However the measurements from the image only permit a marginal increase in the weight of the second stage. It was also clear that such marginal increases would not affect the location of the impact point of the second stage in any significant way. The weight of the third stage of course would be a major determinant of the trajectory of the second stage. It is therefore important to make sure that before engaging in any major iterative process we get a reasonable idea of the weight of the third stage.

The third stage is required to perform two major functions. It has to perform a yaw maneuver to change the inclination plane of the orbit from 88 degrees to the 97.4 degrees required for a sun synchronous orbit. In

addition it has to provide the required velocity to the third stage at the end of the coasting phase to inject it into a near 500 km orbit. The propellant loading of the third stage, the inert mass of the stage as well as the specific impulse are all important parameters for achieving the velocity required.

Based upon the data obtained from the trajectories that matched the first stage impact point we tried to find a crude fit for the propellant loading of the third stage. Using a range of propellant loadings from 1600 kg to 2000 kg for the third stage and a propellant fraction of 0.82 (assumed to be compatible with North Korea's technological capabilities) we estimated the velocity required of a third stage to achieve orbit after carrying out a yaw maneuver to change the orbit inclination plane from 88 degrees to 97.4 degrees.²⁴

A propellant loading of 1800 kg with a third stage mass of 2195 kg seemed to be a reasonable baseline that could not only provide the required velocity from the third stage but would also reduce the pitch down maneuver requirements of the second stage needed to reach the 500 km altitude.²⁵

An 1800 kg propellant and a 0.82 propellant fraction for the third stage yields a vehicle with a liftoff weight

²³ Our preliminary calculations suggest that a velocity correction of about 200 metres per second is required to achieve a 5 degree pitch down of the second stage immediately after the burnout of the first stage when the launcher is travelling at a velocity of about 2 km per second.

²⁴ From the trajectory run with an 89.1 degree pitch angle we could get some idea of the altitude and velocity reached by the third stage during the coasting phase. Using this velocity and knowing that the yaw maneuver requires a 10 degree change and knowing the velocity needed for a 500 km circular orbit the initial mass to final mass ratio can be computed for various fuel fractions and Isp. From these propellant masses and inert weights can be derived that are compatible with the required velocity change for yaw corrections as well as orbit insertion. This exercise also suggested that the specific impulse of the third stage had to be much higher than that provided by a RFNA kerosene stage. The value of 1800 kg propellant and 395 kg inert mass for the stage was obtained through such a process. These values were used only as a starting point for the iteration.

²⁵ Obviously increasing the propellant loading would continue to decrease this altitude. However it may not be possible to accommodate so much propellant given the dimensional constraints revealed by our image analysis. 1800 kg seems to be a reasonable compromise.

79495 Kg.²⁶ This revised configuration was the second baseline for further optimization studies.

This revised configuration of the Unha provided a much better starting point for the iterative process that would match the impact points for the first stage, the shroud and the second stage.

Through a systematic trial and error process an initial pitch angle of 88.93, a launch azimuth of 174 degrees with a sea level specific impulse of 229 seconds for the first stage provided a good match for the first stage impact point.

While we were carrying out this exercise South Korea made public its debris report. The report suggested that the thrust of the four Nodong cluster booster with the vernier engines that constituted the first stage of the Unha launcher was 120 tonnes. We tried to use this value initially in our trajectory analysis. However with the configuration that we had derived from the image analysis work this level of thrust was not very effective in providing a suitable first and second stage performance for achieving orbit. A thrust of about 128 tonnes for the

first stage was found to fit well and this value was therefore used in further iterations.

After fixing the initial launch and first stage parameters we turned our attention to the second stage.

Our trajectory runs indicated that even with the revised third stage parameters, the second stage performance would take the third stage and the satellite to altitudes above the preferred 500 km orbit altitude. It was therefore necessary to pitch down the second stage.²⁷ Along with this it is also necessary to make sure that at the end of the coasting of the third stage (after the second stage has separated) the altitude and velocity are compatible with the needs of the realized 500 km sun synchronous orbit.

So far in all this analyses we had assumed that the second stage used a Nodong engine derivative and a thrust that was similar to that of the Nodong. However as we were trying to carry out our optimization of the second stage with the introduction of pitch down maneuvers for the second stage some new findings were put out in the public domain from a group in Germany. In this they claimed that they had enough evidence to show that the second stage

²⁶ One of the questions as whether the third stage dimensions can accommodate so much propellant. Measurements on the more recent image of the Unha launcher suggest that the third stage of Unha launcher is longer and can accommodate about 2000 kg of propellant.

²⁷ However with the more realistic weights for the third stage the velocity requirements for this pitch down of the second stage become much less making it compatible with the physical measurements obtained from the image analysis.

²⁸ The link to the webinar by Markus Schiller who worked on the December 12 Unha launch is provided by David Wright in the piece that he posted on the net. It is available at <http://allthingsnuclear.org/markus-schillers-analysis-of-north-koreas-unha-3-launcher/> In this oral presentation Schiller makes a case for a lower thrust second stage for the Unha launcher as well as a strong case for an advanced third stage. He also suggests that these stages are designed primarily for a space mission and are not ideal for use as stages in a missile.

was not an engine based on a Nodong missile design but rather an engine that was specifically designed for a satellite launch application²⁸. They suggested that the thrust of this engine was about 15 tonnes or even less. The other conclusions they came to was very similar to our own findings of a low specific impulse first stage, a medium specific impulse second stage and a high specific impulse third stage.

Taking this additional input into account we decided to revisit the performance of the second stage and rework the trajectory once again. We also decided to introduce a pitch correction based on an offset of the thrust axis.²⁹After experimenting with both higher thrusts and lower thrusts³⁰ we came to the conclusion that a thrust of 150000 Newtons for the second stage³¹ along with a pitch down maneuver in which the thrust axis is offset by 3.5 degrees for 25 seconds after second stage ignition gave good results.³²Since the pitch down maneuver also takes away some propellant it was also necessary to increase the specific impulse of the second stage to 269 seconds for realizing the 500 km sun synchronous orbit.³³ We also needed to increase the propellant

loading of the second stage from 8755 Kg to 8866 kg while reducing the inert weight of the stage from 2327 Kg to 2217 kg.³⁴ With these changes we were able to match the latitudes of the impact points for the first stage and second stage quite well. However the longitude error though acceptable was still on the higher side. By changing the initial launch azimuth from 174 to 174.5 degrees the error in longitude was also reduced. The shroud impact point was matched by releasing it at 143 seconds.

Using the improved and revised baseline for the first two stages we could then look at the third stage performance that would yield the required orbit. Starting systematically with no yaw maneuver and a specific impulse of 260 seconds we progressed in a step by step fashion to initiate both the yaw maneuver and the final velocity addition to achieve orbit. For us to be able to achieve the desired inclination and orbit we had to significantly change the specific impulse of the third stage from an initial value of 260 seconds to 288 seconds.³⁵

The trajectory that provides a reasonable fit with the achieved orbit required the third stage to coast for a period of about 475 seconds.

²⁹ **Our model allows for the pitch correction to be done instantaneously with no consumption of propellant or for the correction to be performed by changing the angle of thrust of the main engine and the duration of such thrust.** The thrust axis offset in our trajectory run was set at 3.5 degrees and the duration was fixed at 25 seconds. Both of these can be varied in the model.

³⁰ The original thrust we had assumed was 210000 Newton's for the second stage. We experimented with a thrust of 260000 Newton's as well as 160000 Newton's. The final value we arrived at that gave the best results was a thrust of 150000 Newton's for the second stage. Though the German group had suggested a thrust even lower than 15 tonnes we find that thrusts lower than 150000 Newton's may not be sufficient to achieve orbit.

³¹ This translates into a thrust of 15.29 tonnes for the second stage.

³² This notion of a reduced thrust came from Markus Schiller and our analysis draws upon that. See footnote 28.

³³ The additional specific impulse is also required to match the impact point of the second stage.

³⁴ This means that the propellant fraction of the second stage increases from 0.79 to 0.80.

³⁵ Increasing the propellant loading beyond 1800 kg may not be a feasible option since the measurements from the image put a limit on the tank size. The measurements do not however rule out the possibility that the propellant loading can go up to 2000 kg.

Table 2: Trajectory Reconstruction – Comparison of Initial and Final Vehicle Parameters of the Unha 3

Parameter	Initial Value	Final Iterated Value
Stage 1 Parameters		
Propellant mass stage 1 (kg)	55287	55287
Inert mass stage2 (kg)	10531	10531
Stage mass (kg)	65817	65817
Fuel fraction	0.84	0.84
Thrust Sea level (Newtons) ³⁸	1318598	1254957
Isp Sea Level (seconds)	232	229
Burn time computed (seconds)	95.33	98.935
Area of cross section (m ²)	4.52	4.52
Stage 2 Parameters		
Propellant mass stage 2 (kg)	8755	8866
Inert mass stage 2 (kg)	2327	2217
Stage mass (kg)	11083	11083
Fuel fraction	0.79	0.80
Thrust (Newtons)	210000	150000
Isp vacuum(seconds)	255	269
Burn time computed (seconds)	104.29	155.92
Area of cross section (m ²)	1.52	1.52
Stage 3 Parameters		
Propellant mass stage 3 (kg)	1449	1800
Inert mass stage 3 (kg)	318	294
Stage mass (kg)	1767	2094
Fuel fraction	0.82	0.86
Thrust (Newtons)	93000	93000
Isp vacuum(seconds)	260	288
Burn time computed (seconds)	40	54.66
Area of cross section(m ²)	1.02	1.02
Satellite mass (kg)	100	100
Shroud mass (kg)	300	300
Lift off weight (kg)	79067	79395

The altitude and velocity of the third stage at this point in time are about 499 km and 3.521 Km per second respectively. At this point a yaw

maneuver is initiated.³⁶ The maneuver calls for a total change of 10.66 degrees in 10 steps spread out over 10 seconds.

After the yaw maneuver is completed the third stage engine is fired for another 41 seconds for achieving the final orbit.

Such a trajectory matches well with the known impact points of the first stage, the second stage, and is reasonably close to the final achieved orbit of the North Korean satellite.³⁷ It also suggests that even if the first stage used a RFNA kerosene combination, the second stage has to have an improved engine with a specific impulse of about 270 seconds. Our trajectory simulation also pointed to an advanced third stage that delivers a specific impulse of around 288 seconds.

The Lift-Off Weight (LOW) of this final configuration that best fits the known impact points, the achieved orbit with the simulated trajectory of the launcher was 79395 Kg.

Table 2 compares the original stage parameters assumed for our trajectory analyses and the final values that seem to provide the best fit to the impact points of the first stage, the shroud, the second stage and the achieved orbit.

THE FIT BETWEEN THE RECONSTRUCTED TRAJECTORY AND THE IMPACT ZONES

How good is the fit between the constructed trajectory and the impact areas for the first

³⁶ In practice this calls for a re-orientation of the third stage to align the thrust axis with the required yaw direction (an azimuth change) followed by the firing of the third stage engine. In our trajectory model this is done in steps. The total azimuth change and the number of steps can be changed to achieve the desired inclination change through an iterative process.

³⁷ The trajectory results give an inclination of 97.433 degrees with an apogee of 588 km and a perigee of 494 km. This matches almost perfectly with the parameters put out by footnote 1

³⁸ For a booster stage it is more appropriate to use the sea level thrust and Isp values. Based on empirical data typical variation of thrust with altitude has been modeled and incorporated into our trajectory software. A 10% variation in thrust and a similar variation in Isp values seem appropriate based on a sample of values estimated from typical booster stages. For the upper stages it is more appropriate to use vacuum values of thrust as well as Isp.

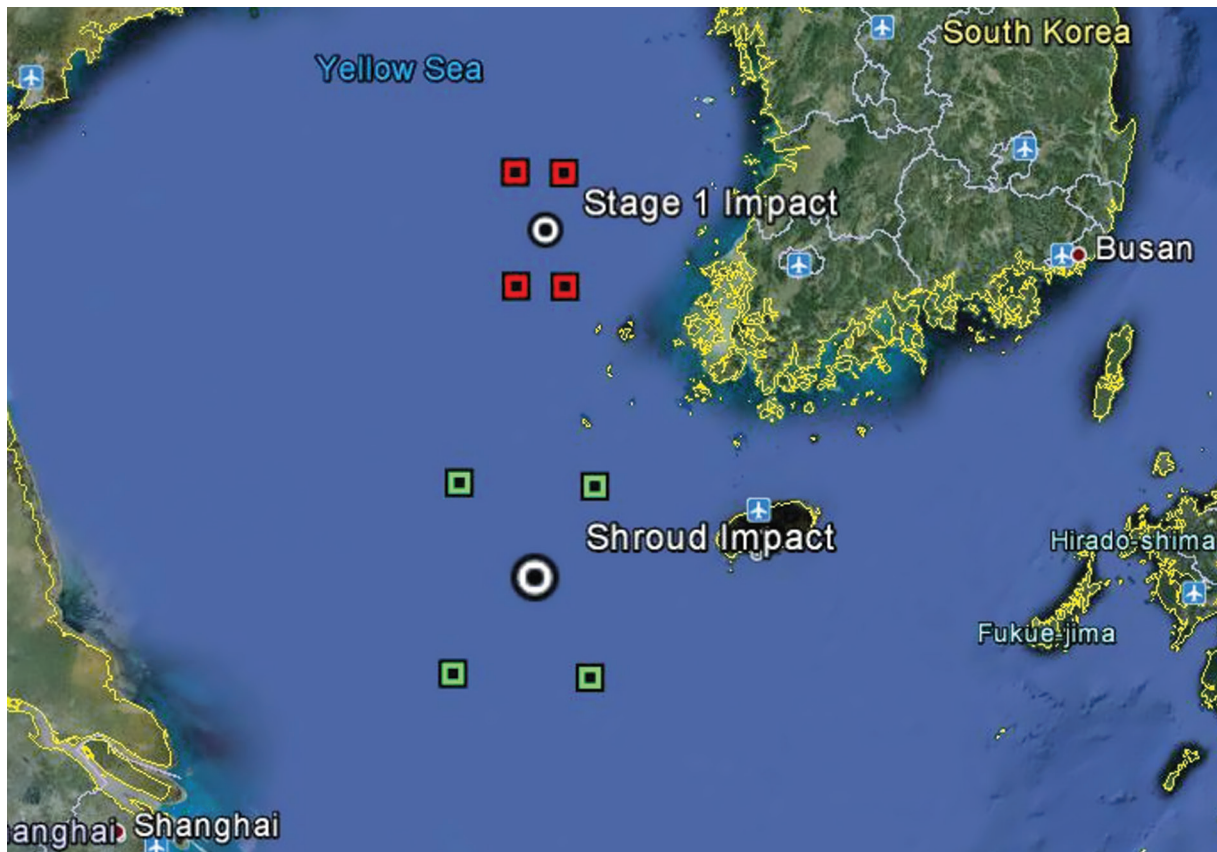


Figure 1

stage, the shroud and the second stage notified by North Korea?

Our final trajectory gives the impact point of the spent first stage as 35.357 N Latitude and 124.771E Longitude. The impact point of the shroud is 33.064 N Latitude 124.756 E Longitude.³⁹ Figure 1 is a Google Earth rendition of the impact point of the first stage and the shroud within the area notified by North Korea for the first stage. **We can see that the trajectory fits well with the mid points of the areas notified by North Korea as the impact areas for the first stage and the shroud.**

Figure 2 shows the impact point of the second stage at 16.895 N and 124.350 E from the final trajectory run within the area notified by North Korea.⁴⁰

We can see from Figure 2 that the match between the trajectory and the midpoint of the impact zone notified for the second stage is very good.

Figure 3 shows the injection point of the satellite using a Google Earth rendition.

The injection of the satellite happens well before the impact of the second stage.⁴¹

The injection point is also seen to be away from the plane of the trajectory of the

³⁹ This matches well with the midpoint of the impact zone notified by North Korea for the first stage which lies at 35.357 N and 124.723 E as well as the midpoint of the impact zone for the shroud which lies at 33.036 N 124.622 E.

⁴⁰ The midpoint of the impact zone notified by North Korea for the second stage is at 16.867 N and 124.261 E.

⁴¹ The injection point of the satellite as per our trajectory is at 27.758 N and 124.268 E.

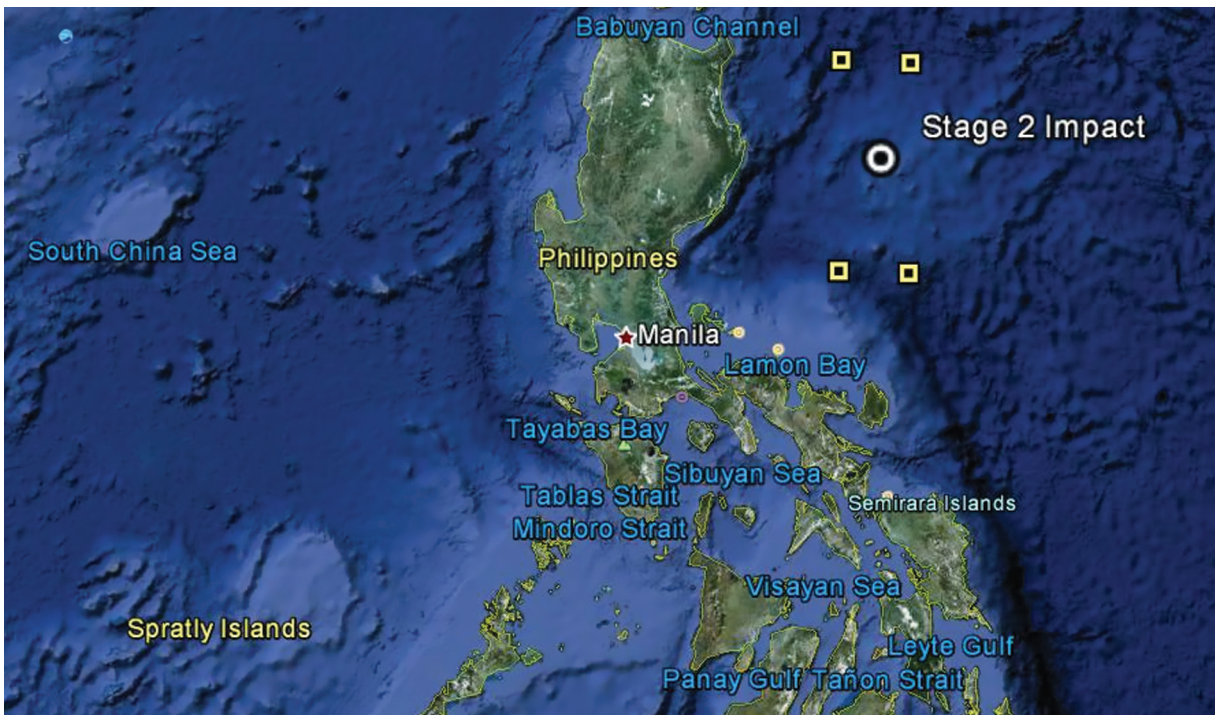


Figure 2

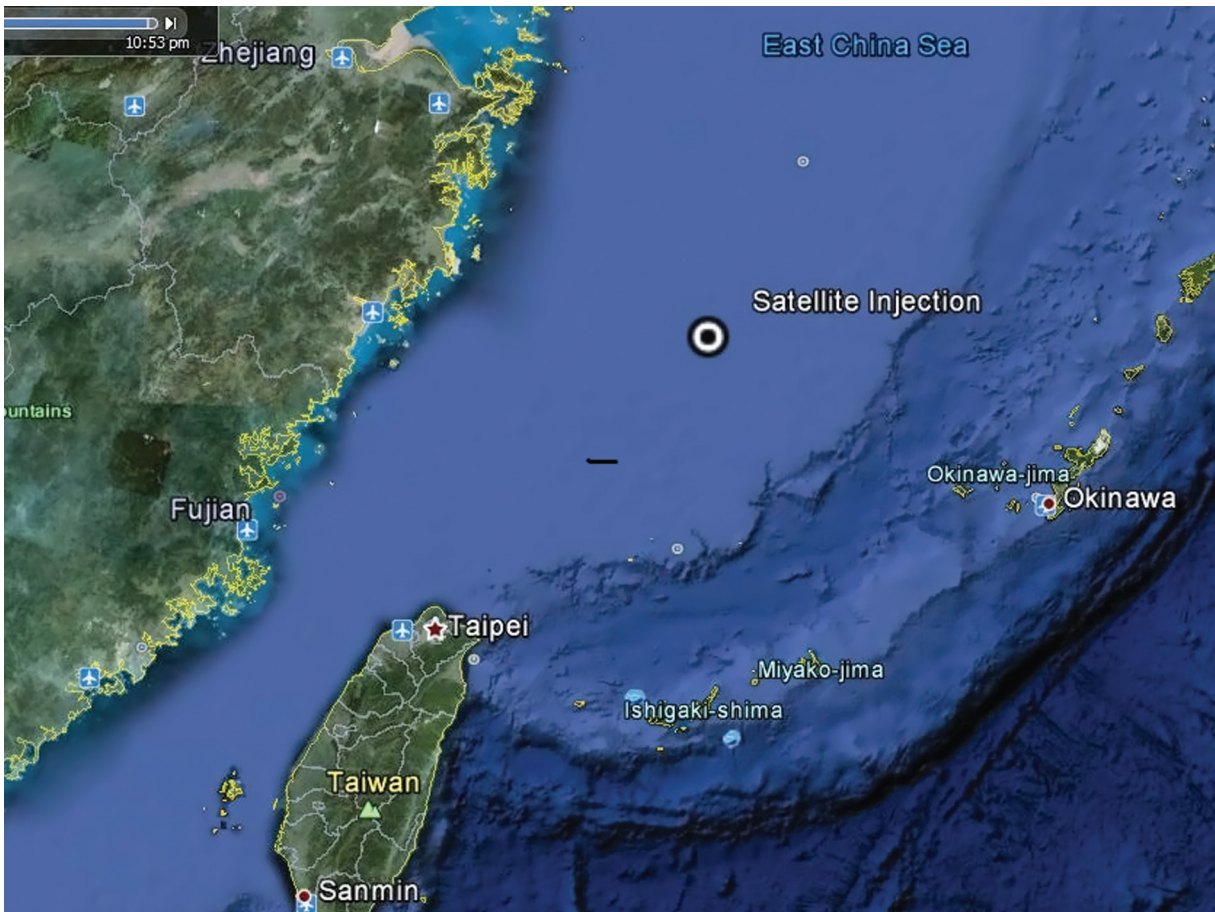


Figure 3

second stage which is consistent with the yaw maneuver required to place the satellite in a sun synchronous orbit.

We can conclude from the above that the reconstructed trajectory provides impact points for the first stage, the shroud and the second stage which are reasonably close to the midpoints of the impact zones notified by North Korea.

Our trajectory results are therefore consistent with the notified impact points for the first stage, the shroud and the second stage. If we can further establish that the orbit achieved by the addition of a suitable third stage is also consistent with the achieved orbit we can infer that our trajectory reconstruction is a reasonable approximation of the actual orbit achieved by the Unha Launcher.

THE RECONSTRUCTED TRAJECTORY AND THE ACHIEVED ORBIT

For achieving a sun synchronous orbit one of the key requirements is the inclination of the orbital plane. For a 500 km sun synchronous orbit this inclination is 97.4 degrees.

Our Reconstructed Trajectory provided the orbit given in Table 3. Estimates of these parameters based on the six line elements provided by NORAD immediately after launch are also shown in Table 3 to use as a benchmark for comparing the results from our reconstructed trajectory.

We can see from Table 3 that our trajectory fits well with the achieved orbit.

Taken together with the fit obtained for the impact points of stage1, the shroud and the second stage the trajectory that we have reconstructed does seem to be reasonably close to the actual Unha trajectory.

Table 3: Comparison of Trajectory and NORAD Orbit Parameters

Parameter	Our Trajectory	NORAD ⁴²
Inclination (Degrees)	97.433°	97.4067°
Apogee (Km)	588.14Km	588 Km
Perigee (Km)	493.92 Km	494 Km
Period (Minutes)	95.2872667	95.5407
Semi-major axis (Km)	6912.030	6918.4 Km
Eccentricity	0.007	0.0061309

TRAJECTORY DETAILS

Figure 4 provides a velocity time line for the operation of the three stages and the insertion into orbit.

Annexure 1 provides a detailed time line of the major events from the final run of our trajectory model.

Figure 5 provides the altitude range plot for the first stage and the shroud.

Figure 6 provides the altitude versus range plot for the second stage.

As we can see from Figures 1 and 2 these impact points are close to the midpoints of impact zones notified by North Korea. This validates to a large extent our reconstruction of the trajectory for stages one and two.

⁴² The relevant orbital parameters have been taken or derived from the six line orbital elements data put out by NORAD with an epoch 12-12-2012 (December 12, 2012) and time 03:52:35 UT. Since the launch time as suggested in footnote 1 was 00:49:00.51 the parameters are those put out immediately after launch.

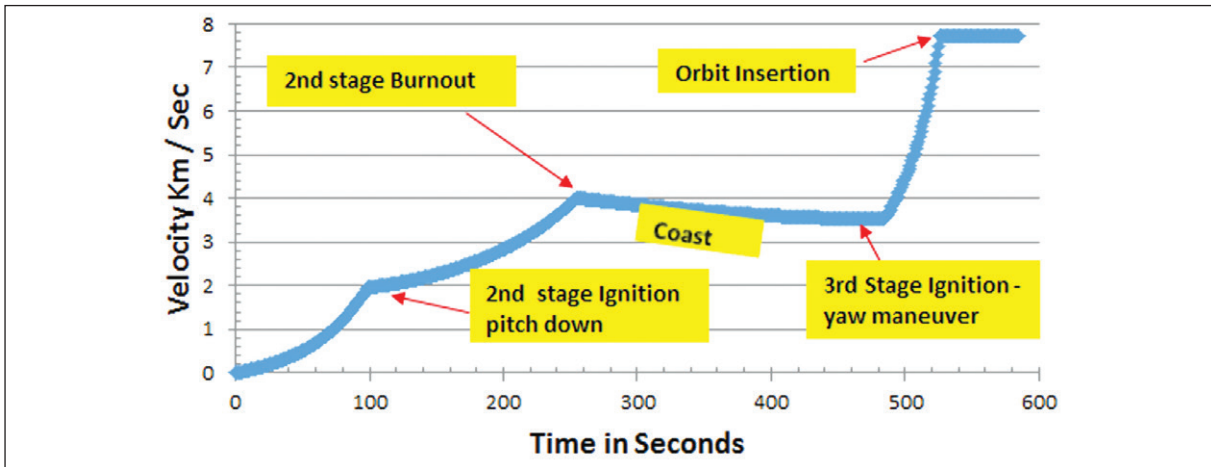


Figure 4: Velocity versus Time Unha

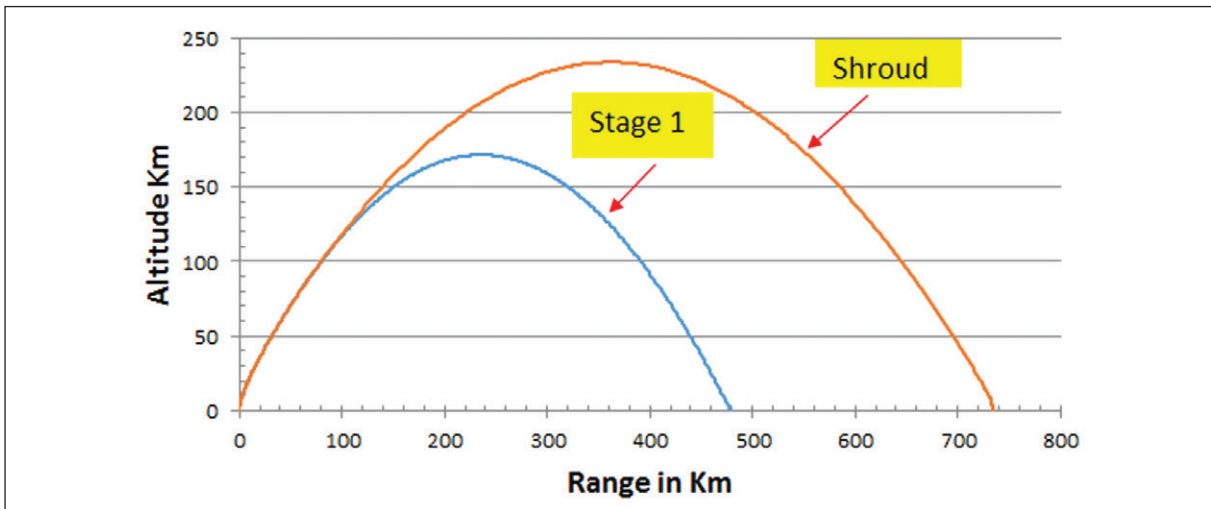


Figure 5: Stage 1 Shroud Impact Trajectories

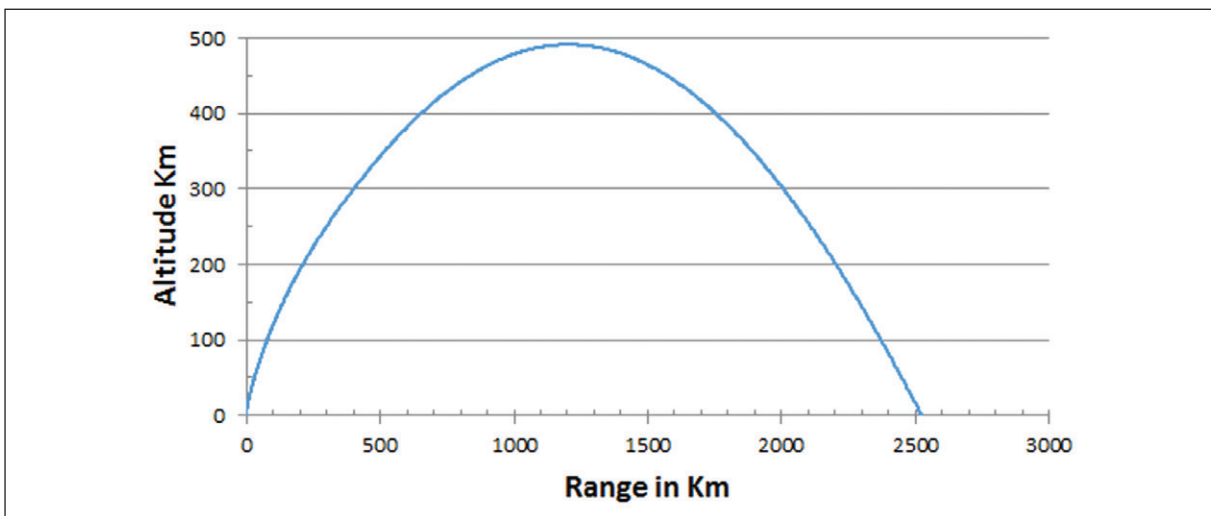


Figure 6: Stage 2 Impact Trajectory

EQUATORIAL CROSSING TIME & THE FIT BETWEEN THE TRAJECTORY AND ACHIEVED ORBIT

One of the issues that has come out of the analysis of Schiller and also validated by our reconstructed trajectory is the performance of the second stage.⁴³ The trajectory suggests that the second stage has a lower thrust engine designed more for a space mission rather than an engine developed for a missile application that has been used to launch a satellite. Is there any way in which we could validate this via our trajectory model?

If the second stage or for that matter any other stage uses a lower thrust engine it will take a longer time for the satellite to achieve orbital velocity. During this time the earth is also rotating from west to east and therefore the injection point will be further away to the east. If we know the launch time and from the orbit we know where precisely the achieved orbit crosses the equator on its downward path for the first time we can get an estimate of the local time of crossing at the equator. This local time of equatorial crossing in the descending mode is a normal parameter specified for remote sensing satellites in a sun synchronous orbit. The longer the duration of the ascent trajectory the later will be the equatorial crossing time in the descending node.

From our trajectory and orbit model and the launch time put in the public domain we tried to estimate the first southbound equatorial crossing local time for North Korea's satellite.

Our trajectory model gives a total flight

time of 526 seconds for the insertion of the satellite into orbit.

The satellite crosses the equator on its downward path at about 967 seconds after launch. The equatorial crossing point has a Longitude of 118.491 E Longitude.

Knowing the launch time, the time taken for the satellite to cross the equator on its first descending node and the longitude of this equatorial crossing point we can easily compute the local equatorial crossing time for the descending node. We can then compare this with the equatorial crossing time put out in the public domain to check whether this is consistent with our trajectory model and the total flight time of the launcher to insert a satellite into orbit.

Our calculation from the trajectory indicates that the first local time of equatorial crossing in the descending node is 08hrs:59 minutes: 5.35 seconds.

According to reference 1 "US tracking then cataloged object 39026 as 2012-072A in a 494 x 588 km x 97.4 degree sun-synchronous orbit with a 0900 local time descending node"⁴⁴. Using the first Two Line Elements (TLE) data put out by NORAD, corresponding to epoch December 12 2012 and 03 52 52.35 UTC, the equator crossing time was also computed by propagating the orbit. The equator crossing time is 04h 16m 35s UTC. Longitude of equator crossing is 70.72deg. Therefore, the Local time of equator crossing as per this is 08h 59m 27s. We can see that our trajectory time of equatorial crossing compares reasonably well with the computed time from the first TLE.

⁴³ See footnote 28.

⁴⁴ Reference 1 provides the detail that the launch took place at 00:49:00.51 UT. This reference based on NORAD data also says that the local time of equatorial crossing at the descending node is 09:00 hours.

There is a difference of about 22 seconds between the trajectory value and the computed value based on the NORAD TLE data. This would suggest that the overall launch duration of the Unha is a little more than that computed by our trajectory. There could be many reasons for this including lower thrusts for one or all of the stages or a longer coasting time.

From all the available evidence which includes the impact points of the first stage, the shroud, the second stage as well as the orbital parameter which includes the inclination, the perigee, the apogee as well as the equatorial crossing time of the sun synchronous orbit achieved we can conclude that our trajectory captures the actual trajectory of the Unha Launcher reasonably well.

Therefore our vehicle parameters for the stages, our assumptions regarding the specific impulses of the various stages and our maneuvers for the different stages to reach the prescribed orbit are consistent with the empirical evidence available in the public domain on the Unha vehicle.

This validated derived information therefore provides a useful basis for making an assessment of North Korea's capabilities in the missile and space launcher domain.

THE UNHA AS A BALLISTIC MISSILE

One of the worries that the US has voiced

publicly is the ability of North Korea's missile to hit various parts of the US. Table 4 provides details of the maximum range of the Unha launched in different directions with a 1000 kg payload. The Table also provides the range estimate that we had made after the failed April 2012 launch of the Unha.⁴⁵

We can see from Table 4 that our current assessment of the range of the Unha Launcher as a Ballistic Missile is about 700 to 1000 Km lower than our earlier estimates based on the failed April 2012 launch.

This reduction is in spite of the fact that the overall mass of the Unha has increased to about 80 tonnes as compared to our April 2102 assessment of about 70 tonnes. The specific impulses of the stages in our assessment of the April 2012 launch were 255 seconds (vacuum Isp), 255 seconds (vacuum Isp) and 260 seconds (vacuum Isp) respectively. In contrast in our current assessment the specific impulses for stage 1, stage 2 and stage 3 are 229 seconds (sea level Isp)⁴⁶, 269 seconds (vacuum Isp) and 288 (vacuum Isp) respectively. This would suggest that the range of the Unha should be more than our estimate for the April 2012 launch. The fact that the range is less with higher quantities of propellants and higher specific impulses especially for the second and third stage validates the point that the Unha configuration is optimized for a space mission

Table 4: The Unha as a Ballistic Missile

Launch Site Location	Payload Mass (Kg)	Launch Direction (Azimuth°)	Range Earlier NIAS Estimate (Km)	Range Current NIAS Estimate (Km)
39.66 N 124.705 E	1000 Kg	Due North (0)	6766 Km	5949 Km
39.66 N 124.705 E	1000 Kg	Due East (90)	7726 Km	6724 Km
39.66 N 124.705 E	1000 Kg	Due South (180)	6787 Km	5965 Km
39.66 N 124.705 E	1000 Kg	Due West (270)	6180 Km	5478 Km

⁴⁵ Footnote 7 Table 2 p 15

⁴⁶ This may translate into a vacuum level Isp of about 252 seconds.

with a significantly lower thrust for the critical second stage. The evidence therefore is clear that the Unha has been specifically designed for a space mission and has not been derived from missile stages that might have been available to North Korea. It can of course use this as a missile though it may not be optimized for such a mission.

Our trajectory also suggests that a due North East launch at an azimuth of about 45 degrees from the Launch site with a 1000 kg payload (sufficient for a nuclear warhead) can reach most parts of Alaska.

NORTH KOREA'S MISSILE AND SPACE LAUNCH CAPABILITIES – AN ASSESSMENT

The available evidence indicates that the first stage of the Unha Launcher comprises a cluster of four Nodong Engines that have a common turbo pump and common tanks for the kerosene propellant and the RFNA oxidizer.

From Table 2 we can see clearly that the first stage sea level specific impulse that best fits the trajectory is only 229 seconds. This is on the lower side of what can be achieved with a RFNA Kerosene oxidizer fuel combination. Even if it were so North Korea has been able to put together a cluster of Nodong engines to provide the initial boost for a space launcher.

It is common knowledge that North Korea developed the Nodong missile from scaling-up of the Scud A technology. This is the technology that they exported to Pakistan and Iran. Evidence from the Unha Launch indicates that North Korea has been able to further scale up and cluster four of these engines to provide a booster for a space launcher. The addition of the

four vernier engines and their integration into a unified stage with autonomous control also represents a significant move away from the crude graphite jet vane control systems of the early Scud A technology used in the Nodong, Pakistan's Ghauri as well as Iran's Shahab 3. Though the technology is old the scaling up and improvements do indicate significant capabilities within North Korea.

We can also see that the second stage specific impulse that best fits the trajectory is about 270 seconds. The thrust of the engine that powers this stage is also much lower than that of the Nodong engine suggesting that the stage and the engine are optimized for a satellite launch.⁴⁷ These indicate that the second stage most probably uses a UDMH RFNA fuel and oxidizer combination that is consistent with the Scud B technology of the Soviet era which used this propellant oxidizer combination to improve the performance of the Scud series of missiles.

The assumption that was made by analysts including us was that the second stage of the Unha missile was powered by a Nodong missile engine. The evidence from the current launch substantiated by other indirect pointers as well as our trajectory results suggest that this stage uses a much lower thrust higher specific impulse engine that has been specially designed for the Unha launcher. Though it would have been easier for North Korea to have used a regular missile engine for the Unha second stage they choose to develop an engine and stage specifically designed for a satellite mission. This once again indicates a substantial in-house capability that has built upon imported or borrowed technology to not only improve it but to use the knowledge acquired to scale-up,

⁴⁷ Schiller – Footnote 28 – was possibly the earliest to point this out.

re-design, develop, test and launch a new stage.

Our Trajectory Model also suggests that the third stage uses an advanced engine with a specific impulse of about 288 seconds. The results also suggest that this is a light weight stage with a high propellant load factor of around 86%. The engine that powers this stage also possibly uses an advanced propellant oxidizer combination such as UDMH and Nitrogen Tetroxide. This propellant and oxidizer combination was not used in the Scud series development. North Korea's possession of this stage indicates that they have the knowledge and capabilities to design, develop, test and integrate such an advanced engine and stage into a space launcher. This is no mean achievement for a supposedly backward country like North Korea.

Apart from these hard technological achievements related to the development of the propulsion units and the stages for the Unha, the launch provides visible evidence that North Korea has been able to integrate these hard technologies with the softer technologies of

mission planning and management of a complex project. The vehicle trajectory including the maneuvers after liftoff, the pitching down of the second stage after first stage separation, maintaining control during the fairly long coast phase, the yaw maneuver of the third stage and the final injection into a fairly good sun synchronous orbit shows a strong and well-developed internal organization of effort within North Korea. The division of work and the integration of these various diverse subsystems and components into a whole launcher and the planning and execution of the launch mission show that North Korea has made commendable progress in its mastery of missile and space launcher products and technologies.

These suggest that North Korea is somewhat more advanced than either Iran or Pakistan in space and missile technologies and products. This more than the actual performance of the Unha launcher as a missile must be a source of considerable concern to North Korea's immediate neighbours as well as the United States.

ANNEXURE 1

Timeline of Major Events Unha December 2012 Satellite Launch

Time (seconds)	Event	Altitude (Km)	Range (Km)	Velocity (Km / sec)
0 sec	Vertical Lift off	0 Km	0 Km	0 Km / sec
5 sec	Pitch Down 88.93, Azimuth 174.5	0.077 Km	0 Km	0.031 Km / sec
53 sec	Maximum Q	11.515 Km	3.88 Km	0.557 Km / sec
98.94 sec	Stage 1 Burnout	53.42 Km	34.80 Km	1.957 Km / sec
98.94 sec	Stage 2 ignition Pitch Down	53.42 Km	34.80 Km	1.957 Km / sec
125 sec	Pitch down stage 2 completed	91.32 Km	70.52 Km	2.08 Km / sec
143 sec	Shroud release	118.54 Km	100.24 Km	2.21 Km / sec
255 sec	Stage 2 Burnout	286 Km	367 Km	4.009 Km / sec
255 sec	Stage 3 Coast	286 Km	367 Km	4.009 Km / sec
475 sec	Yaw maneuver initiated	498.6 Km	1101 Km	3.521 Km / sec
485 sec	Yaw Maneuver Completed	500.53 Km	1133.16 Km	3.517 Km / sec
485 sec	Orbit insertion firing	500.53 Km	1133.16 Km	3.517 Km / sec
526 sec	Satellite separation – Orbit	503.883 Km	1324.08 Km	7.715 Km / sec
967 sec	Equatorial crossing south	521.75 Km	4453.55 Km	7.699 Km / sec

