Response to David Holloway's and Theodore Postol's *Comments on 'Iran's Ballistic Missile Potential'*

By David Montague, Uzi Rubin and Dean Wilkening

We have read "Comments on 'Iran's Ballistic Missile Potential'" by David Holloway and Theodore Postol with great interest and, after careful review of those comments and our original calculations and assumptions, we conclude that our original analysis is valid as it stands. We encourage the careful reader not to be distracted by the tone and confusing calculations presented in the "Comments." The errors in the "Comments" are consistent with the errors that led to an underestimation of Iran's missile potential in the original Joint Threat Assessment (JTA) report and its Technical Addendums, namely a significant underestimation of Iran's solid-propellant missile potential. Regardless of motivation, such an underestimation could lead to policy recommendations inconsistent with US, allied, or for that matter, international security interests.

To begin, we are unclear why the JTA authors ignored Iran's solid-propellant missile program in the first place because, contrary to the claim made in the report—"There is, however, no reliable information at present on the state of Iran's efforts to develop solid-propellant rocket motors and therefore no basis on which to make an assessment in this report."—sufficient information was available in November 2008 when Iran conducted its second unsuccessful test of the Sejjil missile from which one could perform the same kind of photographic analysis that Dr. Postol later conducts in May 2009.[1] It is ironic that the selfsame image released in November 2008 of the Sejjil test actually was used as the cover page of the JTA report, as seen in Fig. 1. Televised interviews with Iran's minister of defense Mohammed Najjer with English translations were available immediately after the test, in which he described the missile and stated that its range was "close to 2000 km".[2] Concern was voiced at the time over this test by the then US administration. In his testimony to Congress following the more recent May 20, 2009 test, the US Secretary of Defense cited a range of approximately 2000 to 2500 km for the Sejjil missile but did not disclose any other performance data. Thus, the statement that there was no reliable information upon which one could base an assessment of Iran's effort to develop large solid-propellant rocket motors at the time the JTA report was drafted is perplexing.

Holloway and Postol raise two basic issues with our original "Response," entitled "Iran's Ballistic Missile Potential," to the JTA report, namely that we provide a misleading portrait of the JTA and its Technical Addendums by selectively quoting from the texts and that our performance estimates of Iranian solid-propellant missiles are based on "hidden and incorrect scientific and engineering assumptions and on large and inexplicable errors in their [our] numerical calculations."[3]

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[1] See for example http://www.youtube.com/watch?v=Yqf2KFsQmLI posted on November 20 2008, as well as clear still images of the November 2008 test such as those shown in Fig. 1.

[2] See www.memritv.org clip No. 1918 "Iran launches a new surface to surface missile with a range of almost 2000 Km" posted on November 12 2008

[3] David Holloway and Theodore Postol, "Comments on 'Iran's Ballistic Missile Potential'," pg. 1

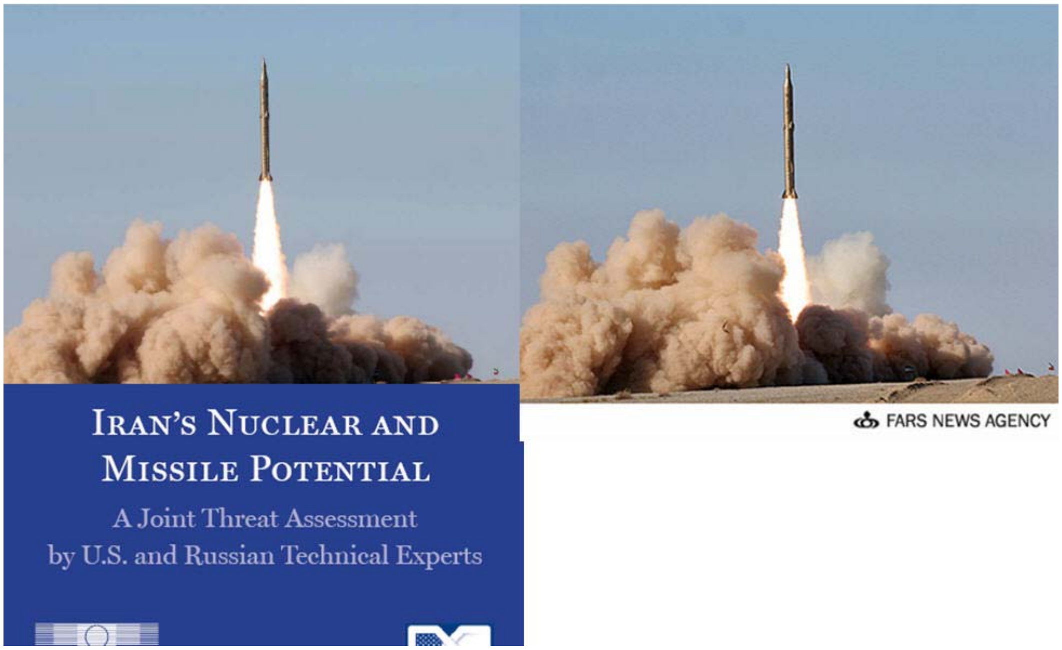

Fig. 1 - Sejjil flight test on November 18 2008. Cover page of the JTA report, May 2009 (left), image released in November 2008 by FARS news agency, Teheran (right).

Regarding the first point, anyone interested in this claim can read the original JTA report and the Technical Appendices and decide for themselves if we have distorted the gist of the report. We do not believe so and instead believe that the report itself is misleading, not our selective quotation from it.

Specifically, the JTA report logically assesses the Iranian nuclear program in section 2 separately from its missile assessment in section 3. While a single statement at the end of section 3.21 states that their assessment of a six to eight year lead time to develop a missile capable of carrying a 1000 kg warhead to a range of 2000 km is dependent on the time to develop a nuclear warhead, the statement that appears in the conclusions to section 3, specifically paragraph 3.39, makes no such qualification. In fact, all of the conclusions in paragraph 3.39 hinge on an assessment of Iran's missile potential, independent of the pace of its nuclear program. Consequently, it is the author(s) of section 3 who failed to make it clear that Iran could develop a 2000 km range missile with a 1000 kg throw weight well before it could have a nuclear warhead capable of delivery by ballistic missiles. Regardless of the time assessed for Iran to develop a nuclear warhead suitable for missile delivery, chemical, biological or conventional explosive warheads of equal or lesser mass could pose a coercive threat to any nation within range and, as such, deserve careful attention.

The technical issues that Dr. Postol raises require a more thorough response. Dr. Postol claims that our analysis contains "serious numerical, technical, conceptual and logical errors as well as numerous errors of fact" and that our analysis contains "computational errors, hidden or misapplied assumptions about rocket technology, and conceptual errors…"[4]

In fact, it is his analysis that suffers from these flaws. To illustrate this, we focus on the two major differences between our calculations and those of Dr. Postol and, thus, address his two major technical points: supposed large numerical errors in our range estimates and higher rocket performance parameters than Dr. Postol believes are warranted. His third point, that our higher performance parameters are inconsistent with our claims about how such performance enhancements can be obtained stems from his misunderstanding of how we arrived at these higher parameters.

Regarding range estimates for ballistic missiles, Dr. Postol claims that our estimates of missile range are "are wrong by a factor of 20 to 25 percent, independent of the erroneous hidden assumptions about technology improvements used in their calculations."[5] In our analysis we compared missile range estimates from three different codes (used independently by the three authors) and our calculations agree to within 2%, a reasonable level of agreement given that we did not try to resolve second order differences between these codes such as the assumed missile drag coefficient as a function of speed or the steering algorithm used for missile fly out. This is an order of magnitude less than the discrepancy reported by Dr. Postol. Moreover, these three codes have been used widely for different missile performance estimates and compare favorably with actual missile flight data. Finally, in an effort to leave no stone unturned, we asked the US National Air and Space Intelligence Center to compare the results of their missile flight code, which is used routinely to estimate the range of foreign missiles, against our calculations. It agrees with our results to within 2%, assuming care is taken to use the same input assumptions. Consequently, we are confident our range calculations are accurate. We have no information about the code Dr. Postol used to compute his range estimates. It would help to resolve this debate if we knew the steps by which he validated his code and "checked and rechecked" his calculations to make sure they are accurate because they appear to contain some glaring inconsistencies.

First, the data in Postol's Table 1 for his Sejjil missile is internally inconsistent. For any rocket stage, the propellant mass, thrust, the specific impulse or *Isp*, and burn time of a missile stage are related by the well known formula,

$$\boldsymbol{Isp = \frac{Thrust}{((M_p \cdot g)/t_{burn})}}, \qquad (1)$$

where M_p is the propellant mass (in kg), t_{burn} is the stage burn time (in sec), *Thrust* is in Newtons, and g is the acceleration of gravity (9.807 m/sec^2). *Isp* is a measure of rocket energy content and efficiency as measured by delivered thrust per unit rate of propellant consumption, and is measured in units of seconds. In the missile flight codes that two of the authors use, the delivered first stage thrust (and, hence, *Isp*) varies as a function of the rocket's altitude because the atmospheric pressure drops with altitude. To include this effect, one needs to know the nozzle exit plane area and make some assumption about the nozzle expansion ratio (typically an ideal expansion ratio). For comparing engineering

[4] Holloway and Postol, "Comments," *Op Cit*, pp. 2, 4, and 16.
[5] Holloway and Postol, "Comments," *Op Cit*, pg. 8.

performance estimates when those details are not available, one typically assumes average delivered or "effective" values for the thrust and *Isp* because the actual values vary throughout the stage burn, especially for the first stage. In other words, the thrust should be the average delivered thrust (i.e., delivered total impulse divided by the stage burn time), and *Isp* is the average effective specific impulse.

Using the Sejjil second-stage values for M_p, *Thrust* and *Isp* given in Postol's Table 1 of the "Comments," one derives a burn time of approximately 56.3 seconds for the second stage, not 50 seconds as listed in Table 1. Therefore, Postol's values for the *Thrust*, *Isp*, M_p and burn time for the second stage of his Sejjil missile are inconsistent, as anyone with a hand calculator can verify. Depending on how one resolves this inconsistency, one gets different missile ranges. The missile labeled as the JTA Sejjil missile in Table 1 of our original critique resolved this inconsistency by assuming Postol's burn time was in error and that his value should have been 56.3 seconds, not 50 seconds, as we clearly state in Table 1 of our "Response." Of course, one could equally well resolve this inconsistency by assuming the thrust or the *Isp* values are in error. For example, if one assumes Postol's second stage thrust, propellant mass and burn time are correct, the second stage *Isp* would have to be approximately 221 seconds, close to the value he gives for the sea level *Isp* of the first stage.

The second issue involves the average values one assumes for Equation 1, especially for the first stage. Since none of Dr. Postol's data include nozzle exit plane areas, we assume he does not vary the rocket's thrust with altitude. Unless one uses a proper average thrust and an average *Isp* that reflect this increase in thrust with altitude, significant range discrepancies occur. When this effect is included, the effective *Isp* for the first stage is higher than the sea level *Isp*, but lower than the vacuum *Isp*.

As we noted in our original response, when we calculate the expected range for the Sejjil missile using the data in Postol's Table 1 we find a non-rotating earth range between 2550 km and 2600 km for a 1000 kg throw weight, not the 2200 estimate provided by Dr. Postol. Our estimated range on an azimuth heading toward central Europe (310°) is approximately 2450 to 2500 km. It should be noted parenthetically that we disagree with Holloway's and Postol's comment that "they [we] agree with our [Postol's] range and payload calculations for liquid propellant ballistic missiles. We calculated the range for the Baseline Sejjil missile, and the ranges for their postulated missiles, using the same techniques and computer programs that were carefully checked and rechecked during the analysis and writing of our Report."[6] We agree generally with the JTA description of Iran's liquid-propellant missile program, but not the range estimates.

How then can the results of our two calculations differ by about 350 km for the Sejjil missile? The explanation Dr. Postol provides is that we are "wrong." An alternative hypothesis is that he uses an incorrect *Isp* for the first stage, second stage, or both. Suffice it to say that the discrepancies in our range estimates can largely be explained either by inconsistencies in Postol's Sejjil stage two data or the use of a sea level *Isp* in the first stage. We were explicit in our choice of parameters to resolve this inconsistency in our

[6] Holloway and Postol, "Comments," *Op Cit*, pg. 13.

original “Response” (56.3 sec 2nd stage burn time) and would suggest that Dr. Postol clarify his “hidden” assumptions about how he resolved this inconsistency in his data.

Anyone wishing to reproduce our results or to explore the implications of using erroneous input data can download from the web a user-friendly flight code provided by Goeff Forden (http://web.mit.edu/stgs/downloads.html). This code, in its current version, uses a constant value for each stage *Isp*, so one must be careful to use the correct effective *Isp* value for accurate range estimates. The effective *Isp* for the first stage of Postol’s Sejjil missile is approximately 238 sec.

For example, if one assumes Postol’s second stage burn time, thrust and propellant mass are correct, the second stage vacuum *Isp* should be approximately 221 seconds, as noted above. Using Postol’s first stage parameters, with an effective first stage *Isp* of 238 sec, and 221 sec for the second stage vacuum *Isp* one obtains a non-rotating earth range of approximately 2150 km, close to Postol’s non-rotating earth value of 2200 km. Another way to produce erroneously low range estimates for the Sejjil would be to assume that Dr. Postol used the sea level value for the first stage effective *Isp*, namely 220 seconds, although in our calculations we cannot get as low as 2200 km (non-rotating earth) using this assumption.

One might wonder why a discrepancy of approximately 350 km, or 15%, warrants such attention. For shorter range missiles, this difference is relatively immaterial. However, if such differences derive from errors in trajectory modeling, they increase non-linearly with increasing range. Therefore, one can be quite far off in estimating the technical performance required for a missile that can threaten Europe, much less the United States, from Iran. The JTA conclusions, and certainly the “Comments” fall prey to such errors and, hence, are pessimistic. These discrepancies clearly impact one’s assessment of Iran’s ability to develop mobile or silo-based IRBMs. For example, when properly modeled, the 66.5 tonne 3-stage missile Dr. Postol claims is needed for 5000 km range using the same vacuum *Isp* and mass fractions in his Table 1 for the Sejjil, it actually flies approximately 6350 km on a westward trajectory (assuming a rotating earth), which easily can be verified using Forden’s code.

While the question of how soon an Iranian ICBM would be feasible is debatable, the issue of an Iranian solid-propellant IRBM is less so. Whether Iran will or will not decide to develop an IRBM is beyond the scope of this paper. However, should Iran decide to do so, it is reasonable to assume that they will go about it in the most cost-effective way, from their perspective. Solid-propellant IRBMs are a logical choice because they can be mobile and they do not require time consuming fuelling operations in the field.

When hypothesizing an Iranian IRBM threat to northern or western Europe, a 5000 km missile is not required. The range from Tabriz in western Iran to London, UK is approximately 3900 km. A missile that could reach London could also reach most of Europe's capitals. The Tabriz district of Iran is large, hilly, and its topography is suitable for hiding ballistic missiles. What such a missile might look like is open to conjecture. For example, Iran could develop larger, more efficient rocket stages, as we assumed in our original “Response,” or they could construct an IRBM with stage parameters closer to those assumed by Dr. Postol, as we will demonstrate. In either case, contrary to his assertions, they can be small enough to be mobile or silo based, contrary to the conclusions of the JTA report.

While we used Postol's vacuum *Isp* for our examination of his pessimistic assessment of the Sejjil missile, we believe it is reasonable to assume higher values, namely that a vacuum *Isp* of 270 sec is achievable by Iran in the not too distant future. The exact timeframe is difficult to predict. Note that the first US solid-propellant ICBM, the Minuteman I, deployed in 1962 (four years after the start of the US solid propellant ICBM program) had a first stage that used first generation ammonium perchlorate-aluminum composite propellant, the same composite propellant assumed by Dr. Postol, and it had an *effective* first stage *Isp* above 260 seconds. The vacuum *Isp* was higher. As noted in our "Response," many solid-propellant space launch vehicles use HTPB (Hydroxyl-Terminated Poly-Butadiene) propellant and have achieved a vacuum *Isp* above 270 seconds. For that reason, when looking at the evolution from the demonstrated Sejjil flight tests to date, we did indeed reflect higher propellant performance. This performance will come about due to some combination of further developments in solid-propellants, increased chamber pressure, and more efficient thrust vector control, and not simply by removing the vanes used to steer the current Sejjil. Dr. Postol seems to think that we believe simply removing the vanes will produce a 20 second increase in specific impulse, which is not the case. Moreover, these developments will not come "quickly" as Dr. Postol attempts to characterize our position. The time frame depends on the level of effort Iran places on its solid-propellant missile program but certainly could be achieved in the next 6-8 years.

Both we and Dr. Postol use total stage mass fractions (the ratio of the propellant to total stage mass), which include other structure and equipment that are carried with each stage. The Minuteman I first stage also had a steel motor case, like the Sejjil is alleged to have, and had a first stage mass fraction of 0.89.[7] The Minuteman I second stage had a titanium motor case. We assumed in our original "Response" that Iran could achieve first stage mass fractions as high as 0.89. Note that a first stage mass fraction of 0.89 does not require filament wound casings, as Dr. Postol implies, but can be achieved with steel casings for large first stage motors. It is well known among knowledgeable experts that stage mass fractions increase, both theoretically and in practice, for larger motor stages even if one assumes the same casing material. Of course, going to lighter casing materials like titanium or carbon filaments can increase the stage mass fraction even further but one need not make this leap to conclude that Iran has the potential to build an IRBM capable of threatening northern and western Europe. We used a value of 0.85 for the second stage mass fraction because it is more realistic. The mass fraction of the second stage of a two-stage missile is not determined solely by the casing material but includes inert masses such as the avionics, batteries, and equipment section and payload support structures and, hence, tends to be lower than one would predict based on a volumetric analysis of propellant loading and casing material alone. We direct the reader

[7] Tony Lin, "Development of U.S. Air Force Intercontinental Ballistic Missile Weapon Systems," *Journal of Spacecraft and Rockets*, Vol. 40(4), July-August 2003, pg 495.

to our original “Response” to review hypothetical IRBMs based on such improved stage performance.

Even if one does not make these assumptions, but stays with Postol’s conservative assumptions reflected in his Table 1 Sejjil characteristics, one can easily design IRBMs capable of threatening most of Europe’s capitals. For example, assuming a larger 1.8 m first stage with a mass of 28,000 kg, a mass fraction of 0.85 and a vacuum *Isp* of 250 sec, and a second and third stage consisting of Postol’s 2-stage Sejjil missile, one obtains a missile with range of approximately 5000 km on a westward trajectory and a total mass of approximately 49.5 tonnes, two tonnes heavier than the fully mobile Russian Topol M ICBM which weighs approximately 47.2 tonnes (not 35 tonnes as erroneously stated in the Addendum). These results can be replicated with the Forden code mentioned above and we invite Dr. Postol and all interested readers to do so on their own. Fig. 2 illustrates the GUI inputs to the Forden code and the resulting range estimate of 4980 km.[8]

Of course, this is not an optimally-staged missile, but it demonstrates that the 66.5 tonne IRBM introduced by Dr. Postol is not required to reach most of Europe. If more optimum staging ratios are used, still using Postol’s vacuum Isp and mass fraction assumptions, a three stage 5000 km missile weighs at least 30% less than Postol’s claim. Moreover, two or three-stage IRBM variants can be constructed with ranges of approximately 3900 km, again using the same conservative inputs used by Dr. Postol (but using them correctly), and the Forden code. Fig. 3 illustrates one such calculation. This three-stage missile has a mass of approximately 32.3 tonnes, clearly light enough to be mobile. We note, parenthetically, that we agree with Dr. Postol that three-stage IRBMs using his performance data are lighter in weight than two-stage IRBMs. And, while staging is a challenge, especially in the high dynamic pressure environment at the end of first stage flight, Iran already has demonstrated successful staging in that environment at least four times on two different vehicles—the Safir and the Sejjil. Whether Iran proceeds with two-stage or three-stage IRBM remains to be seen.

To conclude, we cannot say for sure what caused Dr. Postol’s results to be so pessimistic but the evidence suggests that it was erroneous input data. Whatever the reason, the results are wrong and diminish what started out as a credible analysis. We are confident that our codes are precise and, hence, that our previously presented calculations (and those presented here) are a valid basis for projecting Iran's future missile capabilities. We have further shown that Dr. Postol's claims regarding Iran's inability to develop survivable IRBMs with its present solid-propellant technology are technically inaccurate. Iran already has the wherewithal to develop lightweight, compact, survivable solid-propellant IRBMs that could threaten most of Europe if it so chooses, with the caveat pointed out in our original “Response” that they have yet to demonstrate a reentry vehicle that can survive reentry at these ranges much less a nuclear weapon payload for such a reentry vehicle.

[8] Note that the “loft angle” output of the Forden code appears to be in error, although the range estimates seem accurate. The loft angle for a 5000 km range missile should be approximately 27 degrees not 40 degrees, unless the missile is flown on a lofted trajectory.

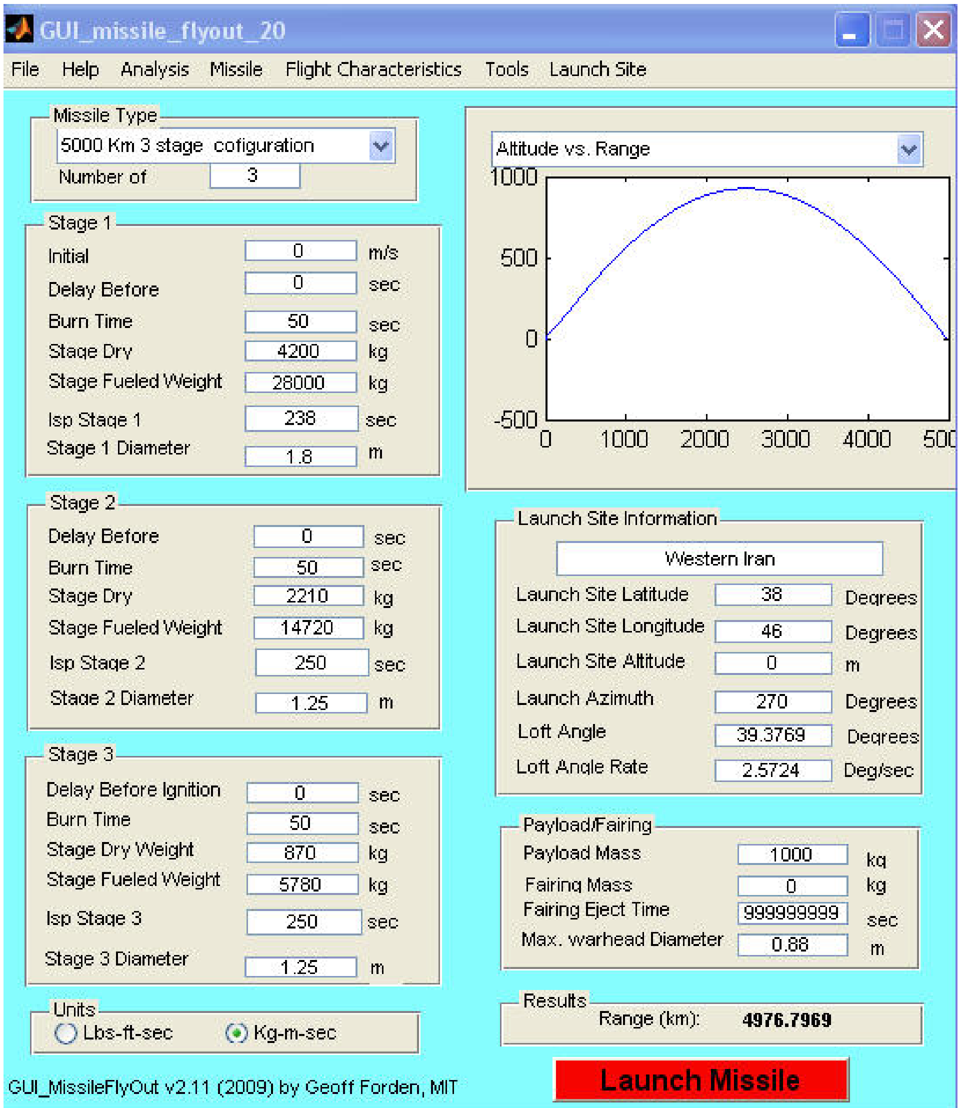

Fig. 2 - Westward range of a three-stage 49.5 ton missile

Those of us who have spent our careers designing, building and flying ballistic missiles, and who developed the methods for accurately predicting actual performance, suggest that Dr. Postol look closer to home for the “serious numerical, technical, conceptual and logical errors, as well as numerous errors of fact” and “computational errors, hidden or misapplied assumptions about rocket technology, and conceptual errors…”. These are not issues of opinion or conjecture, but of demonstrable fact. While the JTA authors’ concerns about the proposed European missile defense deployment and its claim of no imminent ICBM threat are important issues worthy of serious debate, we do not believe that inaccurate technical assessments that misconstrue demonstrated Iranian capability provide a useful foundation for this debate. We cannot divine what

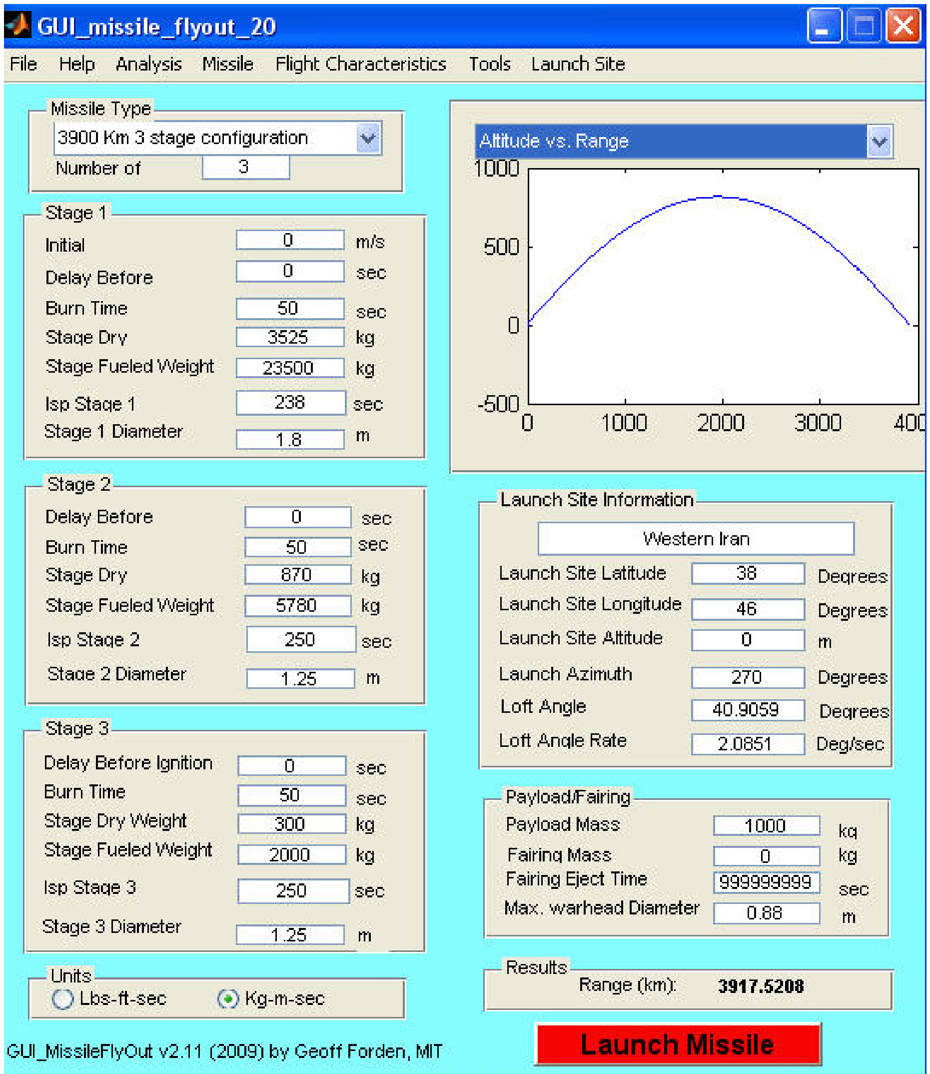

Fig. 3 - Westward range of a three-stage 32.3 tonne missile

Iranian leaders' motives might lead them to do in the future. The signs, however, are not encouraging. It is vitally important that accurate technical assessments are available to policy makers when pondering the implications of possible futures.