Strategic uses for China's Bei Dou satellite system

Geoffrey Forden examines the utility of China's navigational satellite system and considers its potential role in increasing the accuracy of China's strategic missiles.

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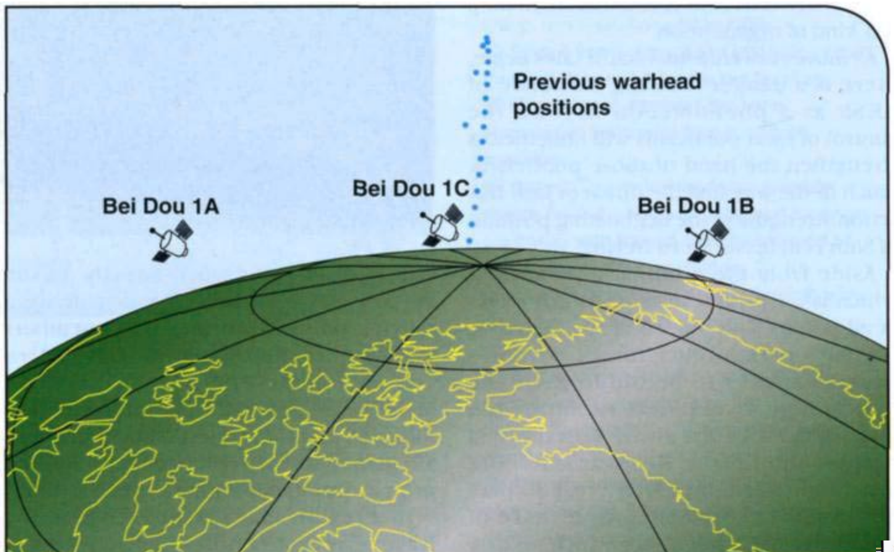


A warhead, launched from China and en route to Washington DC, remains in contact with all three Chinese navigation satellites (Bei Dou 1A, Bei Dou IB, and Bei Dou 1C) for most of its trajectory. This image shows the view looking back from the warhead about 27 minutes after lift-off and moments before Bei Dou 1C disappears behind the curve of the Earth. At this time the warhead is somewhere over Canada; the outline of Greenland is visible to the right.

All graphs by Geoffery Forden

With the launch of the Bei Dou 1C satellite on 24 May 2003, China claims to have completed its constellation of three navigational satellites.

This system is very different from the US navigation satellite system (GPS/NAVSTAR), the Russian GLONAS constellation and the planned European Galileo system. With only three satellites, and in geostationary orbit, the Chinese system can only be used on a regional basis as opposed to the global functionality of the others.

Furthermore, assuming it uses the same operational principles as the other navigational systems - inferring the position of an operator by measuring the distance from a set of satellites - it appears to have only limited utility for navigation of terrestrial users.

All three Chinese satellites were launched from the Xichang Satellite Launch Center, in Sichuan Province, using China's Long March 3A space-launch vehicles, which have the capability to place 2,600kg into geostationary transfer orbit. This is consistent with reports that China has based the Bei Dou satellites on its DFH-3 satellite bus and the final orbit insertion and station-keeping engine, which together have a mass of around 2,200kg. (A satellite's bus contains the basic structure and equipment needed to deliver the essential services such as power and attitude control.)

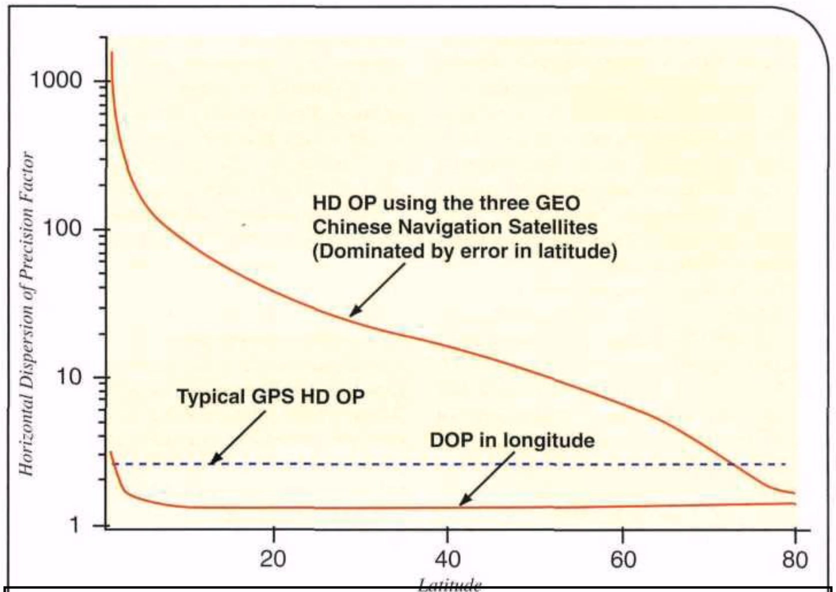
The DFH-3 is a three-axis stabilised communications satellite, capable of keeping its antennas pointed toward the Earth, and has 24 communications transponders in the four to six gigahertz (GHz) range. Basing the Bei Dou on the DFH-3 bus provides the power as well as guidance and control needed for navigation satellite purposes.

China has followed a very methodical entry into space-based navigational satellite operations. Its first declared navigational satellite, known as Bei Dou 1, was launched on 30 October 2000 and took up a geostationary position at 140" east, roughly over the island of New Guinea, creating the eastern most element of its three satellite constellation. Two months later, on 20 December 2000, China launched a second geostationary navigation satellite, which filled a position at 80° east, in the middle of the Indian Ocean. They remained China's only navigation satellites for nearly two and a half years, until the Bei Dou 1C was launched and positioned roughly in the middle of the two existing satellites, at 110.5° east. It is likely that China used this period before the constellation became operational to test the onboard electronics and familiarise itself with their operation.

Naturally, the position of the navigational satellites is important in determining the distances from them to the user and hence the user's position. While these satellites are commonly said to be in geostationary orbits, their positions do vary by amounts significant to navigational systems. During the years the satellites have been on station, China has maintained their position to plus or minus 0.1" in longitude. This is a standard range for station keeping as recommended by the International Telecommunications Union, and at the altitude of geostationary orbits corresponds to a total swing of 150km. These longitudinal motions take place over a period of about a month - the time between the firing of the satellite's station-keeping engine - and so the daily variations are a relatively small two or three kilometres.

However, there are daily variations in position due to the inclination of the satellite's orbit to the equator and the fact that their orbits are not perfect circles. The first two satellites put in orbit now have inclinations of around 0.06", which corresponds to about 50km variations north and south each day, while the newest satellite has an inclination of approximately 0.014". The difference in inclination is caused by the combined actions of the sun and moon (as well as the fact that the Earth is not perfectly round) that have acted on the first two satellites over the two and a half years they have been in orbit. Finally, the fact that the orbits are not perfectly round causes a radial variation of 40km each day.

All of these variations, which seem small on the scale of the satellite's 35,OOOkm altitude, would cause significant errors in position determination unless they are accounted for. Existing satellite-based navigational systems solve similar problems by broadcasting their current orbital parameters - along with a timing signal - to their users, who then calculate an accurate satellite position for use in their location estimation. It seems likely that China uses a similar mechanism.



The geometric factor associated with navigational satellite accuracy **(known** as **HDOP,** for Horizontal Dilution of Precision) is shown here as a function of user latitude for the Chinese navigational satellite system. To determine the actual error, this geometric factor should be multiplied by an error determined by the electronics, atmospheric effects etc, which for GPS systems amounts to about 3m.

Estimating system accuracy

A user of a satellite navigation system can estimate his position in space or on the Earth if he knows his distance from three or more satellites. The accuracy of the estimate is determined by a number of factors including the accuracy of the electronics, effects associated with transmission through the Earth's atmosphere, how accurately the satellite positions are known and their geometry.

Using more satellites increases the accuracy of the position estimation, however positioning accuracy can also be increased if the satellites are ■widely spaced across the user's sky. In fact, four satellites can almost achieve the theoretical maximum accuracy, given the electronics and other factors used, if three of them are equally spaced along the horizon - in other words, separated by 120° - and the fourth is directly overhead of the user. Moving any of these satellites away from this optimal geometry worsens the best attainable accuracy.

Of course, determining the distance from the user to each satellite is not an easy matter. To do this, GPS, GLONAS and Galileo satellites broadcast a signal that contains not only the parameters for their orbit but a time signal generated by a highly accurate atomic clock on board. When the user's receiver registers the times from all the satellites, they will in general all be different because of the time delay the radio waves experience in travelling between the user and the different satellites. If the user has a highly accurate clock that has been synchronised with the

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clocks on the satellites then he can infer the time the radio signals have spent travelling to him. This in turn can be used to calculate the distances separating the user from each of the satellites. If, as is generally the case with present systems, the user does not have a highly accurate synchronised clock with him, then he must use the signals from the satellites to determine his local time. This amounts to taking a sophisticated average of the satellite times but requires at least one additional satellite - for a minimum of four satellites - to determine both the local time and position.

China's system, with a total of three satellites, would require the user to have an atomic clock or some other constraint, such as knowing that the user was at sea level, before it could be used. This latter type of constraint makes the system almost meaningless for most terrestrial applications except the navigation of ships. Since that can already be done to a reasonable precision without satellite-based navigation, it will not be considered in the rest of this article. We will assume that the user carries a rugged, compact, and highly accurate clock or can synchronise a less expensive clock soon enough before use that it does not contribute a significant error.

Atomic clocks have become much more common in recent years, and China must have succeeded in either making or obtaining space-qualified atomic clocks to orbit in its navigation satellites. Nevertheless, it is doubtful that either an infantry platoon or even a tank could successfully operate in the field with one. However, it is conceivable that an aircraft could carry an atomic clock on board and synchronise cheaper clocks that could maintain the required accuracy for the several minutes required after a bomb is released.

The geometry of the satellites, as seen by the user, plays a considerable role in determining the accuracy of the system. China's three satellites in geostationary orbit present a geometry that is far from optimal. If the user is near the equator, the three satellites appear to form a line that passes directly overhead. They are fairly well placed to determine longitude but are very poorly placed for measuring latitude or altitude. In fact, at the equator the Bei Dou constellation's geometry makes it about a thousand times less accurate than the GPS/NAVSTAR system for determining latitude. This assumes that the errors arising from electronics, atmospheric distortion and other sources are the same for both systems. (Inevitably, there will be an error associated with the user's atomic clock unless it undergoes frequent updating as do the clocks on board the satellites, but this is ignored here.) Therefore, the error ellipse associated with a user on the equator would be at least 10m east and west, and 3,000m north and south. Measurements of altitude would also be considerably worse than GPS/NAVSTAR measurements by a factor of 10.

As the user moves northward, the north-south accuracy actually improves, as does the altitude determination, at least to some extent. This is because the geometry of the satellites appears to be better distributed. As the user moves north, the satellites appear closer to the horizon, better approximating the optimum geometry. A user over Taipei, the capital of Taiwan, would have a longitudinal accuracy of about 10m but still have a north-south accuracy of approximately 100m - considerably better than on the equator but still insufficient for guiding aerial bombs. This improvement in accuracy continues as the user moves north until at about 80" latitude, where the longitudinal accuracy is comparable with typical GPS/NAVSTAR measurements, again assuming that all other sources of error are about the same between the two systems. Interestingly enough, the accuracy of the system improves still more at northern latitudes if the user's altitude is increased by several hundred kilometres.

Future improvements?

These accuracies are not sufficient for most terrestrial applications and are certainly not acceptable for the applications that China's national space agency has stated, which include rail and road transportation. However, it is possible for China to augment the current constellation with additional satellites that could give it an acceptable accuracy. One way, if China wanted to continue this system as a strictly regional system, would be for it to launch an additional four satellites in what are known as Molnyia orbits. These orbits are highly elliptical, with altitudes ranging from just over 1,000 km at their point of closest approach to nearly 40,000km at their farthest, and take 12 hours to complete.

Orienting the orbits at an inclination of roughly 63° prevents the orbits from slowly drifting off station to either the east or 'west. Positioning four such satellites would ensure that there was always at least one satellite near the optimum position for navigational purposes.

If this adjunct constellation were added to China's navigational system, it would remain a regional system and yet have accuracies within factors of two or three of GPS/NAVSTAR. Furthermore, it would remove the necessity of the user carrying his own atomic clock since there would be at least four satellites visible at any given time. While China certainly has the technical capability to orbit such a satellite, it has never placed a satellite in a Molnyia-type orbit before. Considering China's deliberate pace at developing weapons systems, it is likely that if it chose to add satellites in Molnyia-type orbits, its first step would be to orbit a single Bei Dou satellite. Then, for a period of time, it could exercise the various functions such as attitude control - keeping the same face of the satellite toward the Earth while the solar-panels are pointed towards the sun - and orbital station-keeping and tracking in this new type of orbit for at least a year. Only then would it orbit the other three satellites in Molnyia orbits.

Attitude control and satellite tracking might prove the most difficult operational aspects of Molnyia-orbit navigational satellites for China. As mentioned above, the orbits for navigational satellites must be known fairly well since any errors in orbit determination feed directly into the errors in a user's position measurement.

The ground control station for a geostationary satellite can use a number of tricks to measure the satellite's position to a much higher accuracy than can a third party observer. Timing a signal to the satellite and back can be used to determine its radial distance to a very high degree. Also, 'lobing' - the process of measuring the relative return from two radio antenna patterns that have slightly different axes - can determine the angular position of the satellite to a remarkable degree. China has undoubtedly developed these two techniques to the required accuracy for the geostationary Bei Dou satellites over the last two years, but would need to develop different operational techniques for Molnyia satellites.

Applications and implications

The utility of a navigation system, and what applications it can support, is determined by its accuracy. Without obtaining a ground receiver for China's system and analysing the

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signals beamed down to Earth, it is difficult to make an estimate of die system's absolute accuracy. However, it is possible to make an estimate of the system's best possible accuracy given the geometry of the satellites. We know that if China's navigational satellite system is not further augmented, it will have an accuracy considerably worse than any of die other systems now operating or planned for the near future.

So-called smart munitions, such as aerial bombs or cruise missiles that use navigation signals to steer towards their targets, need fairly high accuracy to be effective. For instance, it is generally assumed that US JDAMS, a GPS-based guidance system installed on gravity bombs, has an accuracy of about 10m - roughly the accuracy of the military version of GPS itself. If a satellite-based navigation system's accuracy is significandy worse than 10m, it would make little sense to use it since gravity bombs using high-accuracy inertial navigation systems, those systems that use high-precision gyroscopes, have about 30m accuracy. Of course, a particular country might find it very expensive to manufacture the required high-precision gyroscopes but odier techniques, such as 'dive-bombing', can improve a conventional gravity bomb's accuracy to approximately the 30m range, at least during bombing practice. China's navigational satellite system, as it now stands, could not be used for aerial bombs.

It is conceivable, however, that China could use the existing constellation of three satellites to aid in cruise missile strikes against Taiwan. For instance, it is possible China has found it difficult to produce accurate inertial guidance systems that measure the distance along the aircraft's flight path, but are fairly accurate in cross range measurements. For instance, it is possible China has found it difficult to produce accurate inertial guidance systems that measure the distance along the aircraft's flight path, but can produce systems that are fairly accurate in cross range measurements. If that is the case, then the existing system's ability to precisely measure longitude might be an advantage for the eastward missile paths if they attacked Taiwan. However, the most unambiguous application of this system is likely to be improving the accuracy of China's strategic rocket forces.

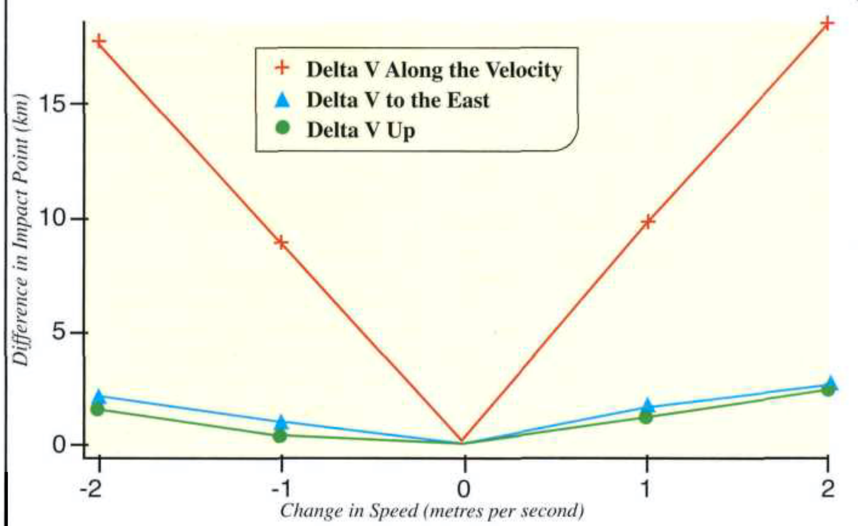
Use with strategic weapons

China would have to more than double the number of its existing satellites and put them into Molnyia orbits that it has no experience with if it intended to produce a regional system that could even come close to the accuracies of existing systems such as GPS/NAVSTAR.

It seems paradoxical that a system too inaccurate to be used for guiding conventional munitions could be used to improve the accuracy of strategic weapons. However there are two ways in which the Bei Dou system could be used to improve the accuracy of Intercontinental Ballistic Missiles (ICBMs) to substantially better than lkm. One method, using a velocity measurement to determine the shut-off point for the main engines, turns out to be impractical. A second method, of guiding a post-boost vehicle or bus, could improve the accuracy of Chinese ICBMs to better than lkm, as well as give China a Multiple Independently targetable Re-entry Vehicle (MIRV) capacity.

As has been learned from the US-Soviet experience, missile accuracy, nuclear weapon yield and nuclear posture are inherently bound together. So, before examining how the Bei Dou navigation system could be used to improve ICBM accuracy based solely on the constellation's geometry, it is worth considering the context of China's nuclear posture.

This relies on a small, survivable retaliatory force that would target an opponent's population centres. The country's current nuclear stockpile is estimated to consist of approximately 20 operational ICBMs capable of reaching the USA. These are the Dong Feng 5A, or DF-5A (also known by NATO as the CSS-4) two-stage, liquid propellant missiles with a range of 13,000km. Each missile is believed to carry a single thermonuclear warhead in the two to three megaton (MT) range, although China has reportedly started and cancelled several programmes to develop MIRV technologies. Stored unfuelled in tunnels, the DF-5As are said to be able to be moved outside and onto their launch platforms and can be readied for launched within 60 minutes. Some analysts believe that China is modernising its nuclear forces and that the DF-5A will be replaced with a solid-fuelled missile, perhaps as soon as 2005.



Distances between impact points and the target for various small changes in velocity for ICBMs from China to the USA, which typically have speeds over 7,000m/s.

Various accuracies have been reported for the DF-5A, ranging from 500m Circular Error Probable (CEP) - the radius within which half the incoming warheads would land - to 3,500m. Multi-megaton warheads could destroy any city if they were delivered by missiles with accuracies anywhere in this range. (A 3MT nuclear warhead would flatten all the buildings within a 6.5km radius and cause fires and death significantly farther than that.) However, if China did MIRV its missiles, it would need to produce and deploy smaller, less massive nuclear devices with consequently smaller yields. A possible yield for such a MIRVed warhead might be in the 150 to 350 kiloton (kT) range. In that case, these weapons could destroy all the buildings within 2.5km to 3km radius, and still ignite fires and kill people much farther away. At these lower yields, China might well feel that it would need to improve its missile accuracies if they were closer to the larger estimates. However, even if its missiles have CEPs closer to the lower estimate of 500m, China would need to develop a bus that could be guided to roughly the same accuracy if it was going to use those smaller yields effectively against multiple cities.

Targeting accuracy and velocity control

The guidance and control functions on an ICBM have a daunting task. After firing its engines for nearly four minutes, reaching a burnout speed of over 7000 m/s, and experiencing accelerations over seven times that of gravity, the missile must have placed its payload in a velocity slot smaller than plus or minus 6cm/s. Such small differences in velocity can make a significant difference to the actual trajectory flown. For instance, increasing the warhead's burnout velocity by 6cm/s ends up increasing the peak altitude the warhead reaches by about 100m; a difference in altitude that continues to increase over the rest of the trajectory and adds to the final difference in range.

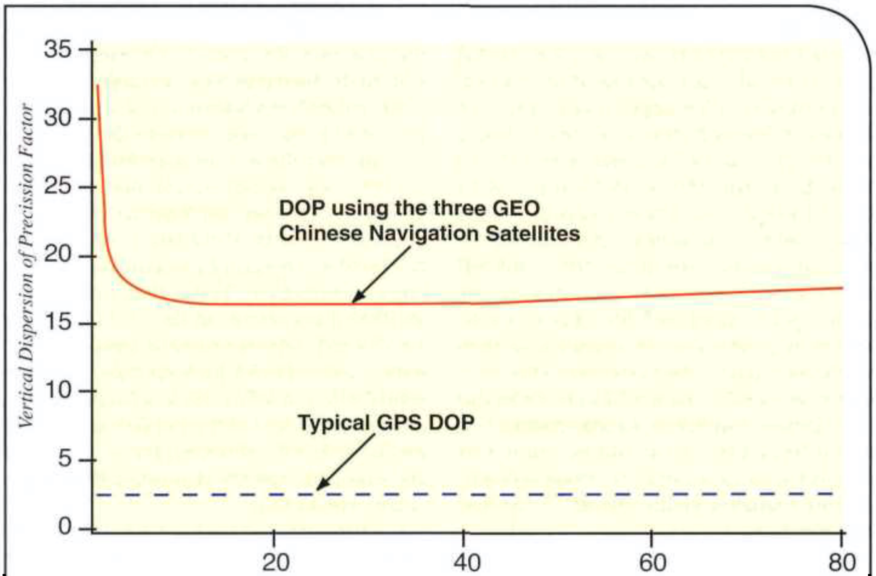
Since the DF-5A does not have a post-boost vehicle to make corrections to the payload's velocity after the second stage burns out, the guidance and control system must terminate the thrust of the second stage to the required accuracy. Controlling the range of the warhead corresponds to controlling the burnout velocity to better than one part in 100,000 if accuracies in the order of 500m are desired. This is probably easier for the liquid-fuelled DF-5A than for more modern solid-fuelled missiles, since a liquid engine can throttle down in the last few seconds of its flight, thereby reducing the acceleration and making it easier to determine the proper engine cut-off time.

If China does switch to a solid-fuelled booster as part of its modernisation programme, the difficulties in accurately controlling the burnout velocity will probably be increased. Accurate thrust-termination can still be accomplished, for instance, by the same mechanism that Minuteman and Poseidon missiles used: thrust-termination ports or passages at the upper end of the missile motor that are blown open with explosive cord. These are used to suddenly reduce pressure and hence combustion and thrust in the motor. Of course, the missile's guidance and control system must still very accurately determine the proper time for thrust determination and would have to do this at its highest accelerations, a circumstance that exacerbates any velocity errors.

One way that China might use its navigational satellites to improve the accuracy of its missiles would involve measuring the Doppler shift - the tiny change in frequency of a radio signal that is proportional to the missile's speed - of signals the satellites beam to Earth. Thrust could then be terminated at the precise time that the missile reached its desired speed and direction. Furthermore, the three satellites in the Bei Dou constellation would allow the Chinese to measure all three components of the missile's velocity. Not only could they measure die speed along the trajectory but they could also measure the cross-range errors.

This mechanism has been used before: Germany not only experimented with using Doppler-shift measurements to shut off the V-2's engines during the Second World War, but actually deployed some missiles with such a cut-off. Eventually, however, Germany developed reliable, high-accuracy accelerometers that were operationally more convenient than the radar-based cut-off scheme. Of course, China too could use ground-base radars to determine engine cut-off, if that proved desirable, since the missile is still visible from the launch site at burnout. However, having the missile's guidance system measure its velocity relative to the three satellites would allow the Chinese to eliminate all the complications associated with very high frequency transmissions (in the gigahertz range) through the atmosphere.

The big difference, however, between a Chinese ICBM and the short range V-2 is the velocity measurement accuracy required. As noted above, if the Doppler shift is going to be used to determine the engine cut-off, it needs to measure velocity differences of several centimetres per second. However, it takes a finite amount of time to measure a Doppler shift since the process can be thought of as comparing two very similar waves and looking for the differences. The measurement devices on the missile would have to take about half a second to measure the velocity to an accuracy of 6cm/s, assuming the satellites were broadcasting in the 6GHz range; a frequency we know they are capable of using. If China used either a lower frequency or required a better accuracy - one corresponding, for instance, to a 50m CEP - the period required to measure the Doppler shift would be increased.



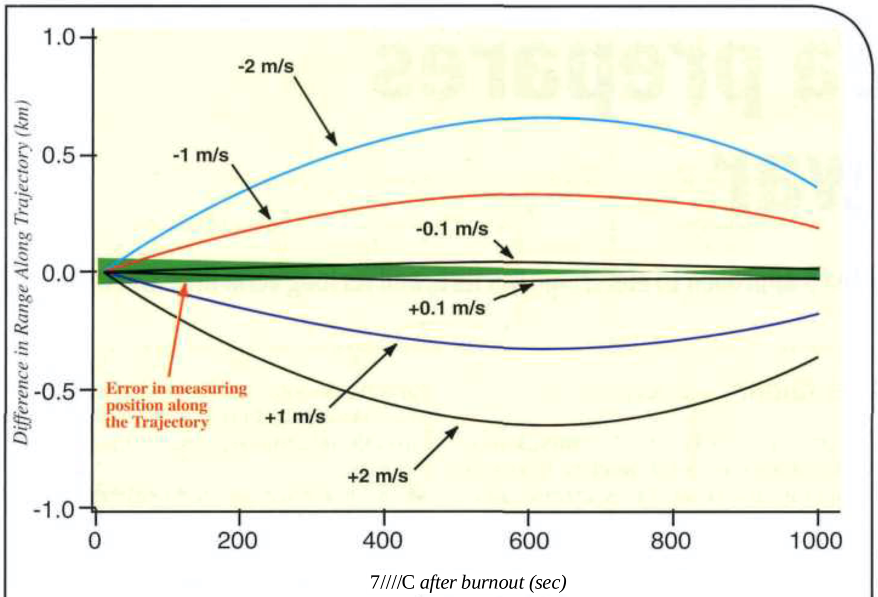
The geometric "dilution of precision", or DOP factor in the local vertical direction is given as a function of user longitude for China's satellite-based navigational system. To determine the actual error, this geometric factor should be multiplied by an error determined by the electronics, atmospheric effects etc, which for GPS systems amounts to about 3m.

During the half second required to measure the DF-5A's velocity to the required accuracy, the missile would change its velocity by about 35m/s; significantly more than the 6cm/s accuracy that is being sought. It would even be difficult to measure that warhead's velocity to the required accuracy after burnout, since gravity alone changes the velocity by about 4.5m/s during the time the Doppler shift is measured. China would have to increase the broadcast frequency of their navigational satellites by at least a factor of 1,000 before it could measure the velocity to the required accuracy in a convenient time. From this, we can conclude that China cannot use its navigational satellites to improve the accuracy of its ICBMs using this method.

Measuring position, inferring velocity

China could use its three navigation satellites to improve the accuracy of its ICBMs by measuring the position of a post-boost vehicle a large number of times after burnout. This method would make full use of the fact that trajectories for warheads with even slightly different velocities travel measurably different paths through space. In this scenario, China would use its standard accelerometer to terminate a missile's thrust, perhaps seeking only accuracy on the final velocity of lm/s or so. This corresponds to a target accuracy of almost 10km and is known to be within China's technological capability, at least for liquid-fuelled missiles.

China could afford this inaccuracy in velocity if there was a post-boost vehicle carrying the warhead or warheads capable of changing velocities by several metres per second - an amount requiring only a modest engine and associated fuel capacity. After the main booster's burnout, the bus would first determine its positions over a period of time long enough to distinguish trajectories whose velocities differ by only a few centimetres per second. This would take at most 600 seconds and possibly significantly less. At that point, the bus would unlock specialised accelerometers and set them to the conditions determined by the satellite-based navigational system or it could simply reset the main inertial guidance unit. Either method would negate any errors the guidance system might have accumulated during the powered flight of the main boosters. The new guidance set would then be used by the bus to control its engines as they correct the vehicle's speed. It could also be used to change the bus' velocity a number of times; a warhead would be released at each new trajectory if the bus was MIRVed.



Changing the velocity of a Chinese warhead along its polar trajectory by very slight amounts (on the order of lm/s out of 7,000m/s total speed) produces measurably different trajectories. This graph shows the differences in range as a function of time after burnout for trajectories differing by these small amounts. These differences get significantly greater than the errors associated with measuring the warhead's position using China's navigational satellites, which is shown in green.

The most unambiguous application of this system is likely to be improving the accuracy of China's strategic rocket forces.

A warhead or post-boost vehicle would be visible to all three satellites for over 27 minutes of its flight. (Figure 2 shows the view looking backward from the warhead just before the three navigational satellites disappear behind the Earth.) This is important because it allows a long period of time for the bus to determine its position a large number of times and infer its velocity to a very high accuracy. A land-based navigational system could not give this extended period of measurement because it would quickly disappear below the Earth's edge as the vehicle moves along its trajectory.

It appears that the post-boost vehicle needs this time to determine its velocity if it is going to reach the required accuracy. Figure 3 shows the differences along the trajectory, as a function of time, for various warheads travelling at slightly different velocities and compares them to the error of the Bei Dou navigational system as a function of time after burnout. The estimated error for this position is roughly comparable to the positional differences over the first several hundred seconds after burnout. However, since the system can make a measurement of the bus' position every second or two, it is eventually able to differentiate these velocities. Trajectory altitude differences can also be incorporated in this determination. It is interesting to note that the system's estimated range error is smallest at roughly the same point that the ranges are most differentiated, at about 700 seconds after burnout.

Some might object that this system's geometry is so oriented towards polar trajectories that China could not test it. Trajectories that are more east-west, as China's tests of its ICBMs must be, could not obtain the same accuracies because the geometries of the three Bei Dou satellites would be so poorly positioned. However, China could test these satellites in their guidance control mode by using other satellites in polar orbits. The orbits of such satellites are similar enough to an ICBM that China could gain substantial operational experience by changing their orbits based on Bei Dou guidance.

China's nuclear posture

While the theoretical capability of a system cannot be used to determine whether it will be used in a specific fashion, it is significant that China's satellite-based navigational system is well suited to guidance and control of ICBMs and is poorly suited to conventional and terrestrial uses. If the Bei Dou system is intended for improving the accuracy of its strategic missiles, it is worth considering the possible implications for China's nuclear posture.

In the context of the US-Soviet nuclear relationship, improved accuracy has been associated with first strikes against either nuclear forces (destroying missile silos before they launch) or against command and control facilities. China, however, would have to undergo a major acquisition programme, not just a modernisation programme, if it wished to attain a first strike capability. A first strike against US Minuteman silos would require at least 500 warheads: one for each silo under START II limits. Even if China MIRVed its ICBMs with three warheads, this would require an eight-fold increase in missiles, not to mention the 500 nuclear warheads needed. Of course, the USA would still have a small number of bombers as well as the entire Trident fleet for retaliation. Even a strike against command and control facilities would be problematic since the USA has the same infrastructure it developed to withstand a Soviet first strike.

An alternative strategy that China may be pursuing with such a satellite-based navigational system is to facilitate MIRVing its missiles without significantly improving their accuracy. China could be striving to increase the numbers of US cities it could target with a limited, if modernised, missile force. Such a satellite-based navigational system for ICBMs would also make sense as a response to the US deployment of a modest national missile defence system. In fact, because of the length of time it would take to initialise the system, the post-boost vehicles would most likely be manoeuvring after the US space-based tracking systems had determined a trajectory and just before the first interceptors could engage the warheads. Such manoeuvring, in combination with the cheap warhead decoy technology China is known to possess, could be very effective against US ground-based interceptors. •

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