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Chinese Shenzhou 7 "Companion Satellite" (BX-1)

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As part of their mission, the Chinese Shenzhou 7 astronauts released a small "companion satellite," said to be roughly the size of a soccer ball, that carried a camera and had maneuvering capability. Some reports refer to the satellite as BX-1, which appears to stand for *ban xing*, an abbreviated form of the Chinese term for companion satellite, *ban sui wei xing*.

As discussed below, goals of the mission appear to be to take and transmit to earth relatively high-resolution photographs, and to maneuver the BX-1 satellite into an orbit around the Shenzhou Orbital Module as preparation for a docking exercise planned for the Shenzhou 8 mission.

Chinese development of a mini-satellite that can maneuver around a larger satellite has raised some questions about its potential military uses. However, our analysis of the BX-1's guidance mechanism appears to indicate that it could not maneuver at close range around another country's satellite since it does not have the ability to determine the distance to the other satellite to high accuracy. Reportedly in this experiment, the plan was for the BX-1 not to approach closer than 4 km to the orbital module during its rendezvous.

There has been little information available in the West about the BX-1 companion satellite; most of the information presented in this paper was gathered from Chinese media sources around the time of the Shenzhou 7 mission (September 25-28, 2008).

The Shenzhou BX-1 "CompanionSat"

The companion satellite was carried into space mounted on the top of Shenzhou's orbital module, and was released by a spring mechanism at 7:24 pm Beijing Time on September 27, several hours after the space walk (Figure 1). The relative speed of the satellite to the orbital module after release was reported to be 0.65 m/s.[2]

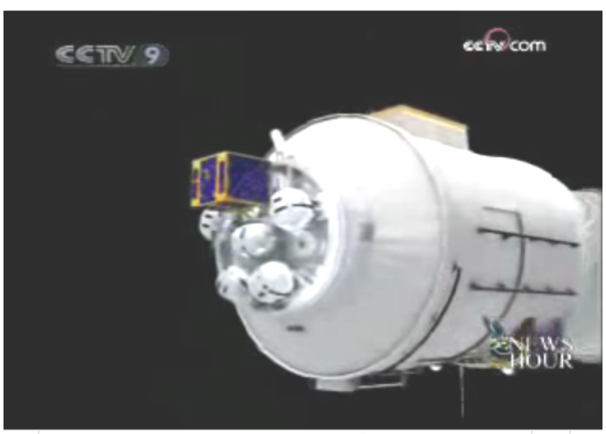

Figure 1: A drawing showing the CompanionSat mounted on the Orbital Module for launch (image credit: CCTV-9, http://www.youtube.com/watch?v=FbJJj2jw8Fc

The BX-1 had a mass less than 40 kg and reportedly carried a camera with a mass of less than 10 kg that had wide-angle and zoom lenses that could take color images from distances of four meters to two kilometers.

The satellite is roughly cubical, about 0.4 m on a side; in comparison, a soccer ball has a diameter of about 0.25 m. Its sides are covered with solar panels (Figures 2, 3, and 4). It has small thrusters for maneuvering; one press report says that the satellite uses an innovative set of “liquefied gas micro thrusters” for propulsion.[3] Other small Chinese satellites are known to use small amounts of hydrazine fuel or compressed gas for maneuvering and typically have 8 to 12 thrusters, each capable of providing less than 1 newton of thrust. The satellite is said to have 3-axis on-board attitude control.

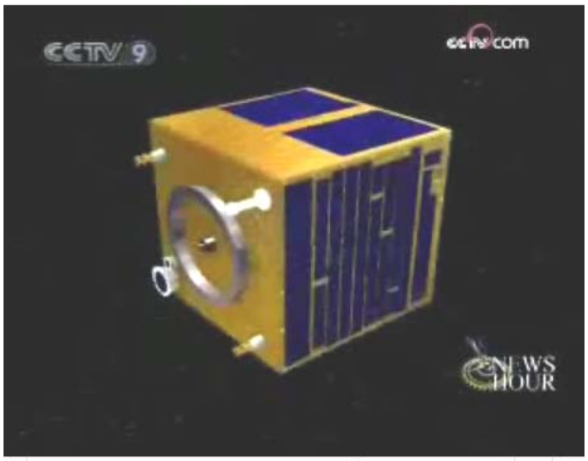

Figure 2: A drawing of the Companion Satellite after being released from the Orbital Module (Image credit: CCTV-9, http://www.youtube.com/watch?v=FbJJj2jw8Fc)

Figure 3: A drawing of the Companion Satellite (image credit: CCTV, http://www.youtube.com/watch?v=Kuflo85U3ig

Figures 4: A photo of the Companion Satellite being prepared for launch. The solar panels are covered with protective sheets. (Image credit: CCTV, http://www.youtube.com/watch?v=Kuflo85U3ig)

Figure 5: The camera lens can be seen on the bottom of the satellite, behind the red ribbon. (Image credit: CCTV, http://www.youtube.com/watch?v=Kuflo85U3ig)

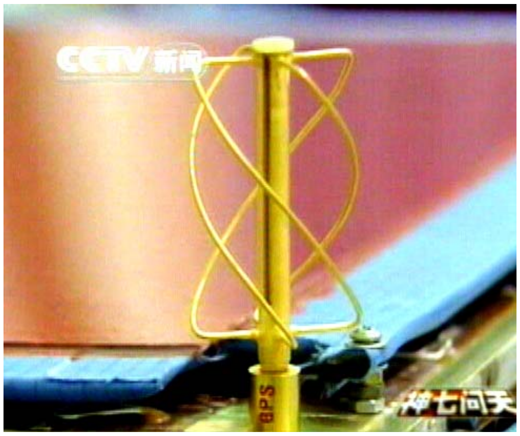

Figure 6: GPS antenna on the CompanionSat.
(Image credit: CCTV,
http://www.youtube.com/watch?v=KufIo85U3ig

Figure 5 shows the camera lens on the bottom of the satellite, near where the satellite attaches to the Shenzhou body. Figure 6 shows the antenna for the on-board GPS receiver, which is apparently on the top of the satellite.

The BX-1 satellite was designed and manufactured by the Chinese Academy of Science's (CAS) Satellite Engineering Center. The chief designer is Zhu Zhencai. It is apparently related to the 88 kg Chuangxin 1 (CX-1) satellite (also called the CASCOM-1), which is also built by the Satellite Engineering Center. The CX-1 is a prototype low earth orbit telecommunication satellite, and was placed in orbit in October 2003.[4]

Figures 7 and 8 show pictures taken of the Shenzhou spacecraft by the CompanionSat shortly after its release.

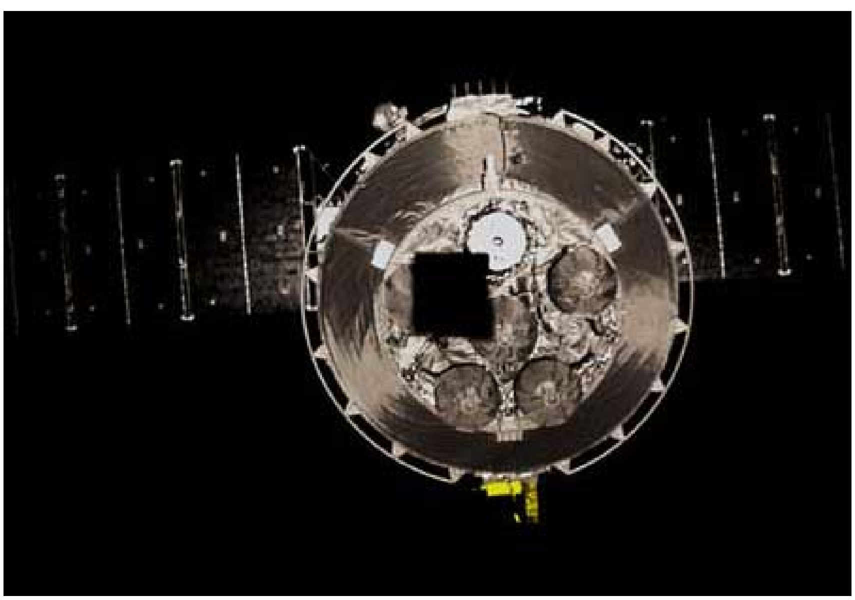
Figure 7: This picture of the top of the orbital module was taken by the CompanionSat 6 seconds after it was released on 27 Septebmer. The black square is the shadow of the satellite. In the background, the solar panels of the service module are visible (http://news.xinhuanet.com/english/2008-10/05/content_10152706.htm).

Figure 8: A photo of Shenzhou 7 from the CompanionSat, reportedly taken 6 minutes after the satellite was released. (http://news.xinhuanet.com/english/2008-10/05/content_10152706_2.htm)

The CompanionSat was used as part of an experiment that tested its ability to rendezvous with another spacecraft and fly in formation with it, and demonstrated a "large store and forward capability for relatively high resolution color images." For this experiment, the Shenzhou spacecraft released the CompanionSat, which drifted away 100 km or more and then maneuvered back to rendezvous with the spacecraft and orbit around it for several hours.

In an interview on Chinese television on September 25, the director of the CAS-Shanghai Satellite Engineering Center, Shen Xuemin, said the goals of the experiment were to test their small satellite technology; to test processes relevant to docking, which will be part of the next stage of the Shenzhou program; and to understand the potential future use of this type of satellite to inspect a larger satellite.

In a CCTV interview on September 28, an engineer with the satellite program stated that the experiment would "provide technical support for developing docking technology," and that this kind of "coordination between spacecraft" would be useful in developing groups of satellites that fly in formation. Similarly, Sheng Jie, deputy general designer of the Shenzhou-7 launch system, was reported as saying "The key part of this research is to make sure the small satellite keeps a safe distance from the Shenzhou spacecraft."[5]

Operation of the CompanionSat

Before the astronauts return to earth, the Shenzhou spacecraft splits into three parts: the re-entry module, which carries the astronauts back to earth; the orbital module, which is where astronauts exit for the space walk; and the service module, which is attached to the opposite end of the re-entry module and contains the main propulsion system for the space capsule. After separation, the orbital and service modules will decay and burn up during re-entry into the atmosphere; at the altitude these objects are orbiting they are expected to decay within a few weeks. Neither will be carrying large amounts of toxic chemicals.

In earlier missions the orbital module carried instruments and remained in space for some months. But for this mission, probably to reduce the mass and provide extra room for the astronauts, much of the equipment was not included on the module (including the solar panels).

The BX-1 was released from the Shenzhou space capsule after the space walk, and it reportedly drifted away to a distance of 100 to 200 km from the spacecraft over the next few days. This distance is consistent with the relative speed of 0.56 m/s noted above.

The satellite reportedly took more than 1,000 photographs, which it transmitted to its ground stations. Zhu Zencai stated that the first photo was sent back in color to test the camera, but that the remaining photos were converted to black and white to reduce the amount of data that the satellite needed to transmit. He was reported as saying "For example, an average color picture is about five megabytes, while a black and white one of the same resolution and articulation is only one fifth of the magnitude, say, one megabyte."[6]

The Shenzhou 7 astronauts returned to earth on September 28. Apparently on September 30 the ground station commanded the BX-1 to move back toward the orbital module. A week later, at 8:14 pm on October 5, after "six orbital change maneuvers" and "under the close monitoring and precise control of the Beijing Aerospace Control Center," the BX-1 was placed in an orbit that allowed it to move slowly around the orbital module,[7] as discussed below. The transit time for the satellite to return to the orbital module suggests that the satellite was only given an approach velocity (relative to the orbital module) of less than one meter per second.

The orbital module was in a roughly circular orbit at about 330 km altitude with an inclination of 42.4 degrees. The BX-1 was reportedly placed in a slightly elliptical orbit with an apogee 4 km higher than the orbital module's orbit and a perigee 4 km lower (see Figure 9). With this arrangement, both objects had the same orbital period, which was just over 91 minutes.

To understand the relative motion of the CompanionSat and orbital module, assume that both objects are located next to each other at the top of Figure 9. The orbital module is following the black orbit and the CompanionSat is following the red orbit, and they are moving counterclockwise. The CompanionSat will be below the orbital module (i.e., toward the earth). Because at that point the CompanionSat is at a slightly lower altitude than the orbital module, its orbital speed will be slightly faster and it will move ahead of the orbital module. When the satellite reaches point P in Figure 9, it will cross in front of the orbital module and move to a slightly higher altitude, at which point its orbital speed will decrease, and it will move back toward the orbital module. When the objects have traveled one-half orbit they will again be beside each other, but the CompanionSat will now be above the orbital module (i.e., away from the earth). On the second half of the orbit, the satellite will fall behind the orbital module, cross behind it to lower altitude, and then catch up to it after one full orbit.

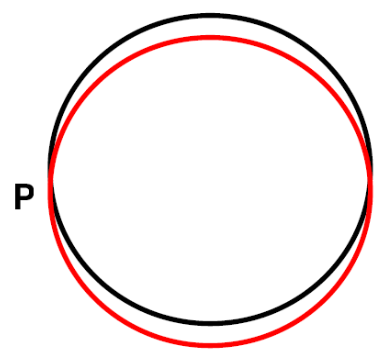

Figure 9: The orbital module follows the black orbit and the CompanionSat follows the red orbit. The orbits cross at point P and at a second point on the other side of the orbit.

From the perspective of someone riding on the orbital module, the CompanionSat would appear to be circling around the orbital module, completing one full transit every time the two objects complete an orbit around the earth. To this observer, the CompanionSat would appear to follow an elongated path so that the separation of the two objects varies between 4 km and 8 km (see Figure 10).

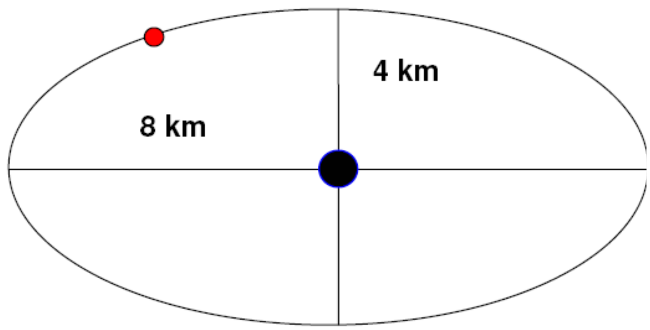

Figure 10: from the perspective of the orbital module (black dot), the CompanionSat (red dot) circles around it on an elongated orbit at a nearly constant speed of about 5 m/s.

The speed of the CompanionSat on this path as seen from the orbital module would be a nearly constant 5 m/s, more than one-thousand times slower than the orbital module's orbital speed of 7.73 km/s (see Appendix A). The relative speed of the two objects scales with their separation, so if the CompanionSat maneuvered closer to the orbital module, its speed relative to the orbital module would decrease. For this reason, this configuration of orbits has been used to prepare for docking experiments. Such experiments are expected on the next Chinese space launch, Shenzhou 8.

An October 5 interview on CCTV reported that the original goal was to have the CompanionSat circle around the orbital module three times, but they later expected it to circle it 10 times. This was apparently because the orbital module was decaying from orbit more slowly than anticipated.

Some press statements about the CompanionSat seem to imply that it has some on-board guidance capability. However, press interviews with high-level officials associated with the project indicate that while the satellite has maneuvering capability, the guidance is done from the ground, based on position information the satellite sends to the ground from its on-board GPS receiver. The press reports also state that the BX-1 cannot communicate directly with the orbital module.

In a September 25 interview on CCTV, Zhu Zhencai, the chief designer of the satellite, said that after the satellite had drifted 100 to 200 km away from the orbital module and the astronauts had returned to earth, then using "its on-board satellite positioning system the companion satellite will send data to the ground station, which will calculate the relative distance between the companion satellite and the orbital module. The ground station will then transmit the command to the companion satellite" to move back toward the orbital module.

Shen Xuemin, director of the CAS-Shanghai Satellite Engineering Center, which built the satellite, said in an interview the same day that "everything connected with this experiment must be done from the ground." He also stated that orbital module does not send signals to the ground so that the ground station tracks the orbit of the orbital module and will put the companion satellite into the companion orbit." He stated that "the ground control center will control the distance between the two spacecraft."

The uncertainties in the ground station's ability to determine the absolute location of the two objects limits how close the CompanionSat can maneuver around the orbital module, which probably explains why they were not intended get closer than 4 km. In order to safely maneuver at closer range, the satellite must have a higher accuracy way of determining the distance to the other object. This separation distance can be determined relatively easily if the rendezvous is with a cooperative satellite, since the spacecraft can compare GPS signals from receivers on-board the two satellites and use differential GPS techniques to determine the distance between them to high accuracy. [8] China is planning to use this method in an experiment in which a small satellite will fly in formation with a larger satellite, initially separated by roughly 1 km (see Appendix B).

Communication relay experiment

The Shenzhou 7 orbital module was also used for a second experiment during this mission. Reports in the Chinese press state that a receiver on the orbital module successfully allowed the orbital module to act as a "client terminal" for China's Tianlian 1 data relay satellite, which China launched into geosynchronous orbit earlier this year. The goal is to place relay communication satellites in orbit to allow China to communicate with its manned spacecraft over a larger part of its orbit around the Earth. Without such satellites, the astronauts would only be able to communicate with ground control when they are in sight of a ground communication station. Since China does not have such stations spread around the globe, without such a satellite any communication with the astronauts would be greatly limited. In previous Chinese space launches, for example, the astronauts reportedly could only communicate with the control center about 12 percent of the time.[9]

Appendix A: Details of the CompanionSat Orbit

We assume here that the orbital module is on a circular orbit of radius $a = R_e + h$ where R_e is the radius of the earth and h is its altitude above the earth. The CompanionSat is placed in a slightly elliptical orbit with apogee a small distance d higher than a and a perigee a distance d lower than a. As a result, the semi-major axis of this orbit is also a, so that both orbits have a period P of:

$$P = 9.95 \times 10^{-3}\ a^{3/2}$$

where a is in km and P is in seconds.

The eccentricity of the CompanionSat orbit is $\varepsilon = \frac{d}{a}$. For the case in which d is 4 km, $\varepsilon = 6 \times 10^{-4}$.

Since the orbital module is in a circular orbit, its orbital speed is $V_{OM} = 631.4\ a^{-1/2}$ km/s, where a is in km. The relative speed V_{rel} of the CompanionSat as seen by the orbital module can be shown to be, to lowest order in ε:

$$V_{rel} = \varepsilon V_{OM} = \frac{d}{a} V_{OM}$$

This equation shows that in the case of the CompanionSat the relative speed of the two satellites is more than a thousand times smaller than the orbital speed of either satellite (4.6 m/s compared to 7.7 km/s). Moreover, the relative speed is linear in d and therefore becomes smaller as the separation of the two satellites decreases. If the separation was 100 m, the relative speed would only be 0.1 m/s. As d changes, the relative orbit would retain the shape shown in Figure 10, with the long dimension equal to $2d$.

The relative speed of the CompanionSat as it circles the orbital module is constant to more than a part in a thousand, since the variations can be shown to be proportional to ε.

Appendix B: The HummerSat-1A Nano-satellite

As an example of the kind of technology used in small satellites, we include here information about another small maneuvering satellite that China is developing, the HummerSat-1A, since there are more details available than for the CompanionSat.[10]

The HummerSat-1A is a 30-kg satellite equipped with a camera and on-board propulsion, which was developed as part of a experiment to demonstrate formation flying between satellites. It was built by a unit of the Chinese Academy of Space Technology (CAST), which also developed the Shenzhou space capsule.[11] The satellite is an octagonal cylinder (see Figure 11) with a diameter of 0.4 m and a height of 0.175 m, making it roughly the size of soccer ball (which is approximately 0.25 m in diameter).

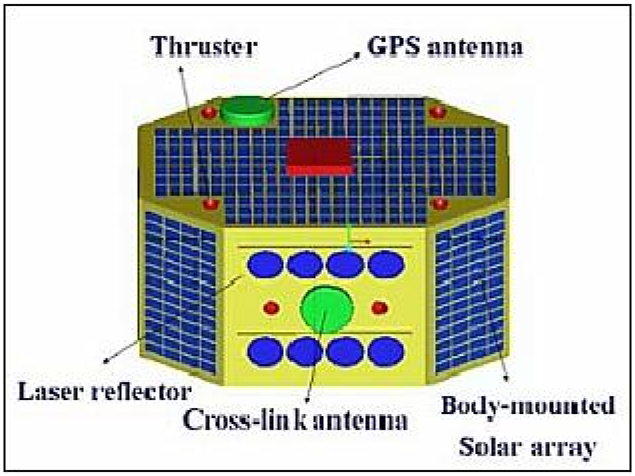

Figure 11: The HummerSat-1A. (image credit: DFHSat)

For maneuvering and controlling its orientation, the HummerSat-1A has 12 small thrusters, each capable of providing a tiny 0.03 newtons of thrust. It has surface-mounted solar cells that reportedly give an average power of about 5 watts.

The satellite is intended to be part of the HummerSat-1 mission[12] (named after “hummingbird” and formerly called Minisatellite-1), in which the 130 kg HummerSat-1 satellite releases the smaller satellite and then flies in close formation with it to test crosslink communication between the two satellites, as well as relative navigation, guidance and control. There is considerable interest in many countries in developing the capability to have satellites fly in formation, since collections of small satellites may be able to carry out the functions of a large satellite, but with various advantages. For example, if one satellite in the formation fails, the rest could continue to operate, and the failed satellite could be replaced much more easily and cheaply than having to replace one larger satellite.

For the HummerSat mission, the small satellite has a structural mass of 25 kg and carries a 5 kg camera.

In the HummerSat experiment, the relative guidance is handled by differential GPS. In this case, the guidance is done on the larger HummerSat-1, as shown in Figure 12. This diagram shows that the smaller satellite sends the information from its GPS receiver through the cross-link to the larger satellite. The larger satellite compares that information with its own GPS receiver, computes the maneuvers the smaller satellite should make, and sends that information back to the small satellite's thrusters. As a result, the HummerSat-1A, like the CompanionSat, does not have the ability to do its own guidance and control calculations.

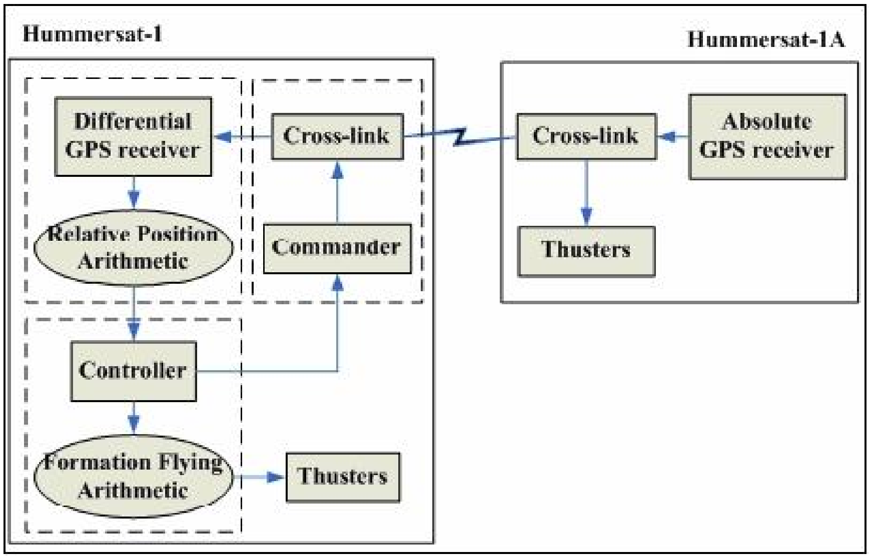

Figure 12: Guidance process for the HummerSats. (image credit: DFHSat)

Endnotes

[1] David Wright is Co-Director and a senior scientist in the Global Security Program at the Union of Concerned Scientists. Gregory Kulacki is a senior analyst and China Project Manager for UCS's Global Security Program.
[2] Lu Lichang, Deputy Director, Directing Designers Branch Office of Tracking and Control System, CCTV interview, 28 September 2008.
[3] "SZ7 Companion Satellite Realizes Five Big Technical Breakthroughs," September 27, 2008, http://news.sina.com.cn/c/2008-09-27/194714509581s.shtml
[4] UCS Satellite Database, 6 October 2008, http://www.ucsusa.org/nuclear_weapons_and_global_security/space_weapons/technical_issues/ucs-satellite-database.html
[5] "Experts dismiss concerns over China's manned space program," Space Travel, September 23, 2008, www.space-travel.com/reports/Shenzhou_Astronauts_Arrive_At_Launch_Center_999.html.
[6] Jing Xiaolei, "Snapshots From Afar," *Beijing Review*, 16 October 2008, http://www.bjreview.com/science/txt/2008-10/11/content_156268.htm.
[7] "BX-1 begins orbiting Shenzhou-VII spaceship," Xinhua News Agency, 6 October 2008, http://www.china.org.cn/china/shenzhouVII_spacewalk/2008-10/06/content_16568297.htm
[8] Differential GPS is a technique in which two GPS receivers can compare their signals and determine the relative position of the two receivers to much higher accuracy that either receiver can determine its absolute position. Differential GPS can give relative locations of two objects to better than one meter, depending on the separation of the two objects.
[9] Tianlian-1, http://en.wikipedia.org/wiki/Tianlian-1.
[10] H.J. Kramer, "HummerSat-1," http://directory.eoportal.org/presentations/6146/15541.html.
[11] The unit that develops and builds small satellites is DFHSat (DFH Satellite Co.).

[12] Xiaomin Zhang et al., "First micro-satellite and new enhanced small satellite series in DFH Satellite Co. Ltd.," *Acta Astronautica* 61 (2007), 234-242.