China's Regional Navigation Satellite System – CAPS

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NASA photo

When it comes to China's satellite navigation efforts, most attention is focused on the Compass (Beidou-2) GNSS that is under development. However, since 2002, that nation has also been working on a regional system called CAPS – for Chinese Area Positioning System. Although CAPS operates on C-band frequencies, rather than L-band in which most GNSS systems transmit, it has a very similar signal structure as GPS. This article discusses the history, system architecture, and advantages and disadvantages of CAPS.

Many navigation satellite systems have emerged since 2000.

GPS is the first global navigation satellite system (GNSS), followed by Russia's GLONASS, reinvigorated in recent years. Europe is developing Galileo, and China is expanding the regional system Beidou to a global system called Compass (also referred to as Beidou-2).

Not all countries can afford to develop a GNSS, mostly because of the high cost, but also because they may not need global coverage. Several regional navigation satellite systems (RNSS) are under development, such as Japan's QZSS, India's IRNSS, and the first phase of Beidou (with completion of an east Asian coverage area currently projected for 2012).

A less well-known RNSS is the Chinese Area Positioning System, or CAPS. CAPS is a "passive" one-way system similar to most navigation satellite systems: satellites broadcast the navigation messages; receivers are only "listeners." (Beidou-1 is a two-way system, the user also sends messages to the control center through satellites).

But CAPS is also different from all the other navigation satellite systems in that the navigation messages are generated on the ground and uploaded to the communication satellites, with the satellites acting only as transponders (see **Figure 1**).

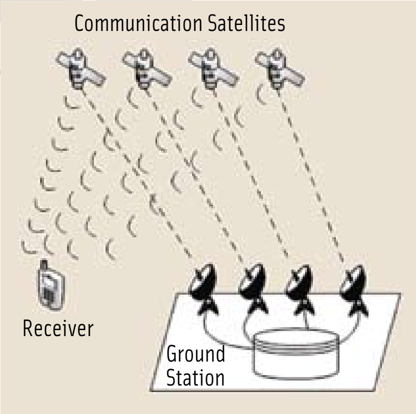

FIGURE 1 The principle of CAPS

History and Basic Concepts

CAPS was initiated in 2002 based on a proposal from the National Astronomical Observatories of China (NAOC), Chinese Academy of Science (CAS).

The CAPS constellation consists of commercial geostationary (GEO) communication satellites and inclined geosynchronous orbit (IGSO) communication satellites. These spacecraft are not traditional navigation satellites: all the navigation-related facilities are all located on the ground.

This system has at least three major advantages:

- Operation does not require the launch of specific navigation satellites, but instead bandwidth can be rented on commercial communications satellites. Hence, the cost is much lower, and the deployment of the system can occur much more rapidly.
- Because all the navigation related facilities, especially the atomic clocks, are located in a ground station, the size of the clocks and their operational environment are no longer big issues. The system can use a larger but more accurate and reliable atomic clock (for the whole system rather than one clock for each satellite), and maintenance is obviously much easier.
- A receiver of this system by definition must also be able use the communications facilities of these satellites, meaning that versatile new applications can be considered for this system that are not inherent in other navigation satellite systems.

It took three years to develop a validation system for CAPS. This system used four commercial GEO communication satellites. (At least three satellite-receiver ranges are needed for a position fix; a fourth range can increase the coverage and provide redundant measurements.)

This type of constellation cannot provide 3D positioning because the satellites are all located in orbit over the equator. Consequently, CAPS equipment designers incorporated a barometer into receivers to provide a height estimate.

The ground station collects pressure and temperature data from weather stations around China and broadcasts the information as part of the navigation messages, which helps calibrate this barometer. The positioning principle is the same as GPS, except for barometer estimating height to provide a 3D positioning result:

$$\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} - c \cdot \Delta t_u$$
$$\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} - c \cdot \Delta t_u$$
$$\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} - c \cdot \Delta t_u$$
$$\frac{x_u^2 + y_u^2}{(a+h)^2} + \frac{z_u^2}{(b+h)^2} = 1$$

where ρ_i is the pseudorange, (x_i, y_i, z_i) is the satellite's position, (x_u, y_u, z_u) is the user's position, Δt_u is the receiver's clock error. a and b are the semi major axis and semi minor axis of the earth respectively.

If the IGSO satellites are available, at least one more pseudorange measurement can be used rather than the altitude from the barometer.

CAPS Signal Structure

In GEO communication satellite systems, C-band and Ku-band are popular for communications, while L band is rare. Because of the significant rain attenuation of Ku-band signals, C-band is the only suitable choice for a navigation satellite system.

Although most such systems use L-band, C-band has advantages and disadvantages for navigation: a C-band signal is less affected by ionospheric delay, less carrier phase noise, and better resistance of multipath. However, as with Ku-band, C-band has larger rain attenuation and larger tropospheric delay than L-band.

Unlike GNSS systems, the CAPS satellites themselves do not carry atomic clocks. However, the pseudoranges used for positioning are the measurement between the satellite and the user; hence, the signal transmission time for that part of the signal path must be known.

CAPS uses C-band for navigation. The two carrier frequencies (downlink) are C1=4143.15 MHz and C2=3826.02 MHz. CAPS also needs two uplink carriers, which are $C1_u$=6368.15MHz, $C2_u$=6051.02MHz.

Similar to GPS, the two frequencies can be used together to correct the ionospheric delay. Despite the difference in carrier frequencies, CAPS has a very similar signal structure to GPS. It also has similar types of codes: coarse acquisition (C/A) and precise (P) codes. A third code — a modulated binary offset carrier (BOC) signal, has also been designed and is believed to be in use.

The C/A-code uses a Gold code at a rate of 1.023 Mcps, and P-code employs a special secure code at a rate of 10.23 Mcps. The broadcast messages consist of ephemeris, time, virtual clock parameters, the pressure and temperature information, wide/local area differential corrections, and integrity information relating to GNSSes.

Virtual Atomic Clock

The standard time reference for CAPS is provided by the master clock — a hydrogen maser, which is located at the ground station. The master clock (UTC) of the National Time Service Center (NTSC) of China calibrates the CAPS clock. The time offset between the master clocks may be broadcast in the navigation messages.

Unlike GNSS systems, the CAPS satellites themselves do not carry atomic clocks. However, the pseudoranges used for positioning are the measurement between the satellite and the user; hence, the signal transmission time for that part of the signal path must be known. The actual range that is measured by the receiver is that from the ground station, which transmits the broadcast messages to the satellite, plus that from the satellite to the receiver.

The relationship of the various pseudoranges can be expressed as

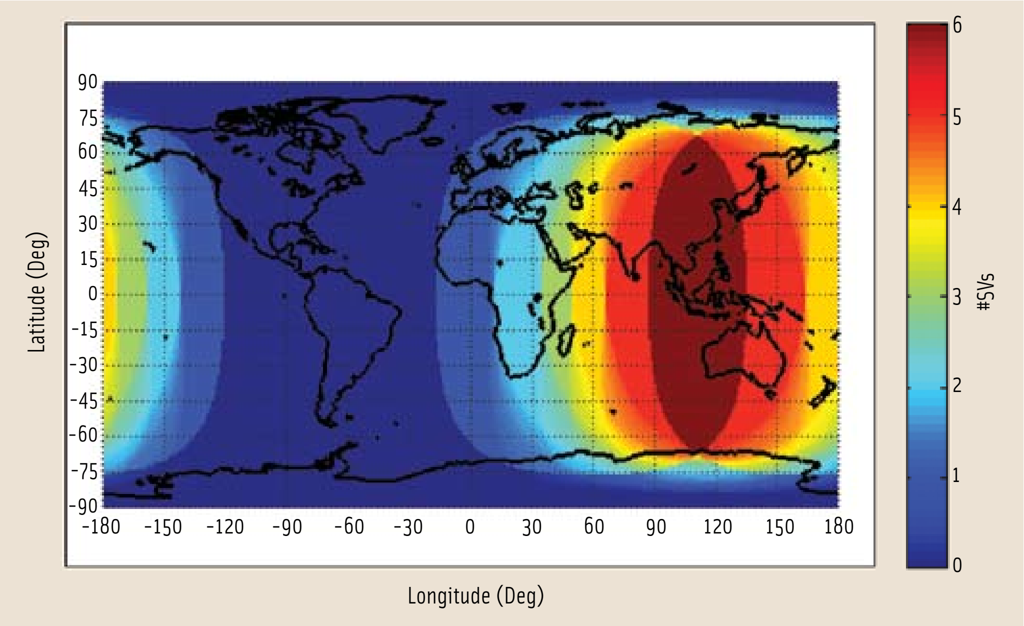

FIGURE 2 Average number of visible satellites (above a five-degree elevation cutoff angle) of the six-satellite CAPS constellation, which consists of two GEO satellites and four SIGSO satellites with inclination of seven degrees

$$\rho = \rho_0 - \rho_1 = \rho_0 - c \cdot \tau_{VCLK}$$

where ρ is the pseudorange from the satellite to the user (required for positioning), ρ_0 is the pseudorange from the ground station to the user (measured), and ρ_1 is the pseudorange from the ground station to the satellite, a term which needs to be removed.

The equivalent expression of ρ_1 is $c \cdot \tau_{VCLK}$. τ_{VCLK} is the correction of a virtual clock that could be considered to be operating on the satellite. This correction is obtained by measuring the broadcast message from the satellite at the ground station (where it originated) to obtain the round trip delay and then subtracting the downlink delay which includes the ionospheric delay, tropospheric delay, and the delay caused by the receive channel on the ground station.

This virtual clock correction includes the uplink atmospheric delay, satellite receiving and broadcasting delay, and so forth. The virtual clock correction model is then created and the coefficients of the model are included in the navigation message.

The major error in the virtual clock correction is caused by the imperfect ephemeris prediction of satellite location because the location is used to calculate the signal downlink delay. However, when the virtual clock error and ephemeris error are considered together in positioning, the combination of these two is smaller than the individual virtual clock error or the ephemeris error, leading to more accurate positioning.

SIGSO

If there are only GEO satellites in CAPS, the 3D position dilution of precision (PDOP) is poor, so that 3D positioning is impossible. This has led to the use of the receiver barometer in the early configuration of the system.

Two methods have been proposed to improve the CAPS PDOP. The first is to launch several IGSO satellites (at least three), which have "figure-8" ground tracks, as used by other systems such as IRNS and Japan's Quasi-Zenith Satellite System (QZSS). (This approach also includes Compass, where three IGSO satellites are proposed). Use of IGSOs can decrease the PDOP significantly.

However, IGSO launches are not cheap; so, a second method was proposed — using retired GEO communication satellites by maneuvering them to so-called slightly inclined geostationary-satellite orbits (SIGSO).

GEO satellites are normally controlled to be "static" at their orbital slot, but many factors — such as gravitational effects of celestial bodies on the GEO —can change the orbits once control is relaxed. Consequently, GEO satellites always carry propellant fuel with which to maintain their orbital location — a technique referred to as station-keeping.

Most of the time, the amount of fuel transported aboard the satellite determines the lifetime of the GEO. In many cases, even if the satellite is otherwise operating successfully, the satellite has to be terminated once it has consumed all its fuel.

If the satellite is no longer controlled, its position will drift. The drift in south-north direction is more significant than that in east-west direction. Indeed, 90 percent of the fuel on a GEO is used to maneuver a satellite against disturbance in the south-north direction.

When a GEO satellite approaches the end of its life but its position in the east-west direction can still be maintained, the GEO in effect becomes a SIGSO satellite. Because the satellite is no longer using fuel to maintain its north-south position but only the 10 percent portion needed for east-west station-keeping, the remaining lifetime of a SIGSO can be extended to 10 times before controllers need to place it into a graveyard orbit. Such a SIGSO satellite can be used in CAPS.

The beauty of a SIGSO is that it has a "figure-8" ground track, meaning it can improve PDOP because it introduces a north-south component into the constellation geometry. The larger the inclination of the SIGSO satellite, the better the PDOP that can be achieved. Another advantage is that a retired GEO satellite can be acquired cheaply.

A simulation of the CAPS constellation, assuming two GEO satellites (located at 59°E and 163°E) and four SIGSO satellites (located at 87.5°E, 110.5°E, 125°E and 142°E respectively) with an inclination of seven degrees.

This configuration provided more than 80 percent of the territory of China with a PDOP of less than 7 (assuming a five-degree elevation cutoff angle). With CAPS, the majority of South-East Asian countries and parts of China and Australia can enjoy PDOPs less than 6. Korea, part of Japan, and half of the territory of Australia obtained PDOPs below 7.

Figure 2 shows the average number of visible satellites (above a five-degree elevation cutoff angle) of the six-satellite CAPS constellation. **Figure 3** gives the average PDOP value a 24 hour period, and **Figure 4** shows the variation of PDOP value at several cities in the Asia-Oceania area over a 24-hour period. More IGSO satellites are still needed to provide even better PDOP.

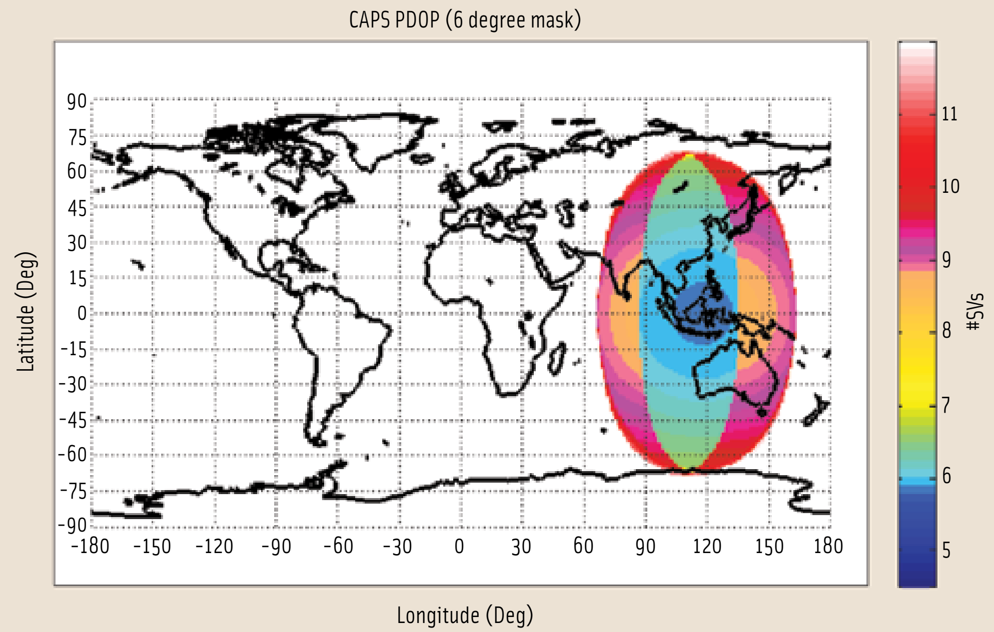

FIGURE 3 Average PDOP value of the six-satellite CAPS constellation over a 24-hour period; white area indicates that the PDOP value is higher than 12.

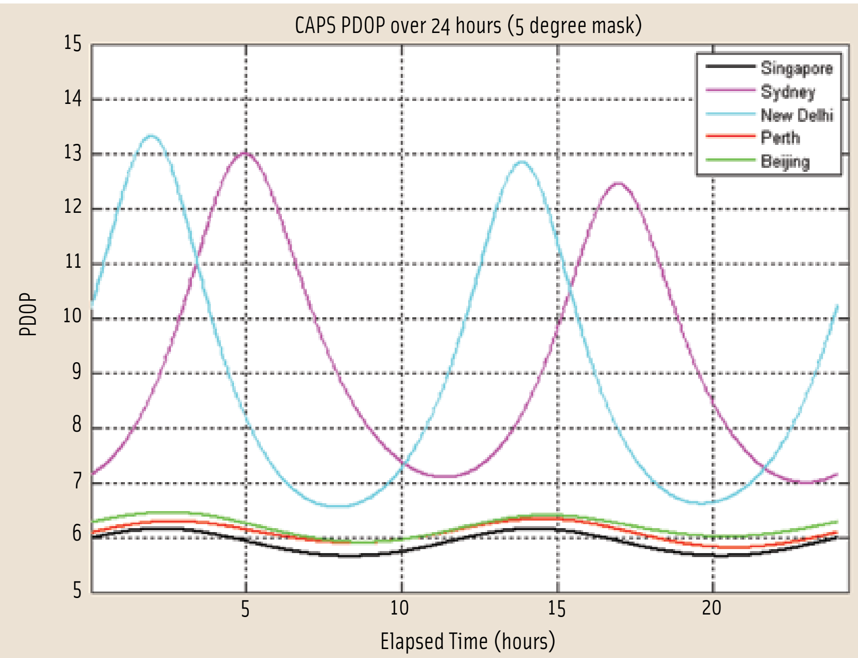

FIGURE 4 Variation of PDOP value of the 6 satellite CAPS constellation at Singapore, Sydney, New Delhi, Perth, and Beijing over a 24 hour period

CAPS: Advantages and Disadvantages

As with any complex system in which numerous trade-offs must be analyzed to achieve an optimal solution, the Chinese Area Positioning System has both.

The advantages of the CAPS system design include the following:

1. CAPS is much cheaper than other navigation satellite systems, for two reasons: the system uses GEO communication satellites, especially retired ones and generates the navigation messages on the ground. Building a CAPS-like system that covered one-third of the Earth's surface would only cost an estimated US$300 million — about one percent of the cost of a full-fledged GNSS.
2. The system can be deployed very quickly. All the important equipment in a traditional navigation satellite can be deployed on the ground. Only several more IGSO satellites are potentially needed in the constellation and those are basically communications satellites, which do not need a special design. To build the validation system only took three years.
3. Use by CAPS extends the lifetime of some communication satellites — in effect, "recycling in space."
4. Because the CAPS spacecraft are communication satellites, they can be used not only for navigation but also for navigation-related communications or redeployed primarily for general communications at any time.
5. CAPS increases the number of navigation satellites visible in the Asia-Oceania area.

6. It has a similar signal structure to GPS (in a different band), making the development of an all-in-one receiver (for GPS, Galileo, Compass, QZSS, and so forth) easier, while making the equipment more robust against interference at any given radio frequency.
7. CAPS was developed for China, but a much larger Asian-Oceania area can benefit from it, especially South East Asia and part of Australia. Japan's QZSS has already attracted much attention from some Asia-Oceania countries, including Australia. Because the CAPS constellation has more satellites and is a civilian system, it also has potential for international collaboration.

On the other hand, CAPS has a number of disadvantages:

1. C-band is used for the data link, making interoperability more complicated than for systems operating at L-band.
2. The system faces the possibility of same-frequency interference from other communication satellites. To solve this problem will require the collaboration of many organizations.
3. Because the satellite is only a transponder, the navigation signal relies on the ground station. If anything happens to the ground station or the uplink, the satellite loses its navigation function. Compared with the other navigation satellite systems, therefore, CAPS is more vulnerable.
4. A barometer may be needed to provide altitude. Local pressure and temperature data around China must be collected and broadcast by the satellites. If other countries want to use this system, this requirement is likely to become a problem. Other countries far from China would have to build their own ground station to generate the broadcast messages.
5. Generally, the PDOP of CAPS is not as good as that of GNSS systems, even if three IGSO satellites were launched.
6. Positioning, velocity, and time (PVT) accuracy is not as good as for GNSS systems. Based on the CAPS validation system (two GEO satellites located at 87.5°E and 110.5°E longitude, two SIGEOs located at 134°E and 142°E, plus a receiver barometer), the static PVT accuracies are as follows:
   a. for standard service: position ~15–25 meters (1σ) horizontal, ~1–3m vertical; velocity, ~0.13~0.3 meters/second; time, 160 nanoseconds
   b. for precision service: position ~5–10 meters (1σ) horizontal, ~1–3 meters vertical; velocity, ~0.15–0.17 meters/second;, time, 13 nanoseconds.
   After the launch of IGSO satellites, the accuracy is expected to improve several times.
7. China has a working regional military satellite navigation system Beidou and it is on the way to expand this into a dual-use global system, Compass, which consists of five GEO satellites, three IGSO satellites, and 27 MEO satellites. Even those people who are working on CAPS agree that Compass will have priority, casting a shadow over the future of the CAPS.

Conclusion

Compass is a GPS-like system. The cost of this system will be tens of billions of dollars, and a debate is still underway in China about whether it is worth developing such a GNSS. The technical barriers, such as the on-board atomic clocks, are a great challenge for the development of Compass.

As a far cheaper alternative, CAPS has attracted many supporters. No matter what we argue about the good or bad elements of this system, it is very impressive to build a RNSS within three years. Where CAPS goes from here may not live up to this early success.

Additional Resources

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