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Introduction to Space Electronic Reconnaissance Geolocation

1.1 Introduction

With the rapid development of aerospace technology, space has gradually become the strategic commanding point for defending national security and providing benefits. As the electronic reconnaissance satellite is able to acquire the full-time, all-weather, large-area, detailed, near real-time battlefield information (such as force deployment, military equipment, and operation information), it has become a powerful way to acquire information and plays an important role in ensuring information superiority [1, 2]. In the early 1960s, the United States launched the first general electronic reconnaissance satellites in the world – *Grab* and *Poppy* – to collect electronic intelligence (ELINT) on Soviet air defense radar signals. Intelligence from *Grab* and *Poppy* provided the location and capabilities of Soviet radar sites and ocean surveillance information to the US Navy and for use by the US Air Force. This effort provided significant ELINT support to US forces throughout the war in Vietnam [3].

Space electronic reconnaissance (SER) refers to the process in which signals from various electromagnetic transmitters are intercepted with the help of man-made satellites, and then features of signal are analyzed, contents of signal are extracted, and the position of transmitters are located [1–5]. The main tasks for space reconnaissance includes: intercepting signals from various transmitting sources such as radars, communication devices, navigation beacons, and identification friend or foe (IFF) transponders, determining the tactical or technological parameters and location, and identifying its type, purpose, and the related air defense system and weapon system; intercepting and analyzing signals of remote control and telemetry and estimating its weapon system performance, experimental situations and development trend; intercepting and monitoring radio communications, analyzing the signal features and determining the location of the transmitters, interpreting and deciphering the communication contents from which the potential military actions and operation plans can be perceived; long-term

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monitoring of the changes in the electromagnetic transmitters and obtaining the information such as electronic equipment development status and rules of force deployment and activities.

According to the intended purpose, the application of the SER system can be classified into radio frequency spectrum surveillance, ELINT, communication intelligence (COMINT), signal intelligence (SIGINT), battlefield surveillance, and characteristic measurement intelligence reconnaissance. The major reconnaissance objects are transmitters from air, space, land, and sea. The major reconnaissance signal types include radio signals, short wave and ultra-short communication signals, satellite communication signals, microwave and troposcatter communication signals, data link signals, IFF signals, navigation signals, and space data link signals. The band of the reconnaissance objects ranges from short wave, ultra-short wave, VHF (very high frequency), UHF (ultra-high frequency, L band, S band, C band, X band, Ku band, Ka band to EHF (extremely high frequency) band, while the frequency can range from 0.3 MHz to 70 GHz.

Generally speaking, SER tasks are mainly conducted by electronic reconnaissance satellites on a low earth orbit (LEO) (which includes a sun synchronous orbit, polar orbit, the orbit with the inclination near the critical value, and an inclined orbit) and electronic reconnaissance satellites on a medium earth orbit (MEO) and a high earth orbit (HEO) (highly elliptical orbit or geostationary orbit), and a near-SER (vehicle in the stratosphere or a suborbital vehicle). The altitude of the electronic reconnaissance satellites on a low orbit is relatively low, most often 300–1100 km with an inclination greater than 50°. Thus a relatively accurate location for the transmitters can be achieved. These satellites can also be applied to monitor the emitters on the sea through the reconnaissance and location of the radar or communication signal on vessels. The reconnaissance can be run with one satellite or a multiple-satellite network. Typical reconnaissance systems are the US *Semos-F* series electronic reconnaissance satellite, the US *White Cloud* series electronic ocean surveillance satellite and the former USSR *Tselina* series electronic reconnaissance satellite. The orbit altitude of a synchronous orbit reconnaissance satellite is generally about 36 000 km. The significant advantages are its wide coverage, stability over earth and all-weather, 7/24 continuous reconnaissance, and monitor of the electromagnetic signals from one particular area on earth. A typical HEO reconnaissance system is the US *Magnum* series electronic reconnaissance satellite. A highly elliptical orbit electronic reconnaissance satellite is primarily used for the continuous reconnaissance and monitoring of the areas with high altitude. It can make up for the disadvantages of poor reconnaissance performance of a synchronous orbit electronic reconnaissance satellite in such areas. A typical system is the US *Jump Seat* series electronic reconnaissance satellite.

As position information is one of the most important parts in the intelligence generated from the electronic reconnaissance (ER) system, location technology plays a crucial role in the SER and determines the means of operation for the entire reconnaissance satellite. This book introduces various concepts, theories, and methods on electronic reconnaissance geolocation in great detail, and discusses the direction-finding geolocation, geolocation based on TDOA (time difference of arrival), geolocation based on TDOA–FDOA (frequency difference of arrival), geolocation by a single satellite based on kinematics, and geolocation based on a near-space platform, and at the same time analyzes and explores in depth the orbit determination of a satellite using direction finding and frequency information from a space platform.

1.2 An Overview of Space Electronic Reconnaissance Geolocation Technology

According to the space location of the transmitters, two types of signals can be intercepted from space: the transmitters on the earth's surface (land, sea, and air) and the satellite transmitters in space. According to different observation platforms, the electronic reconnaissance system can be based on a satellite or a near-space platform. Therefore, three reconnaissance geolocation technologies are discussed here, that is, geolocation of a ground emitter, geolocation of a space emitter, and geolocation using a near-space platform.

1.2.1 Geolocation of an Emitter on the Earth

Through the geolocation of the transmitters of the earth's surface, information from various radars, wireless communication stations, and navigation stations can be revealed, which is rather meaningful and valuable for the military. The earth's surface here is in a broad sense that covers land, sea, and lake surface and low altitude air.

The fundamental characteristic of SER geolocation is to locate the satellite through the intersection between the geolocation line and the *a priori* information of the ground emitter on the earth's surface, as shown in Figure 1.1. According to the number of electronic reconnaissance satellites, the geolocation method can be classified into the geolocation method by a single satellite, the geolocation method by dual-satellite, and the geolocation method by multiple satellites.

1.2.1.1 Geolocation Method by a Single Satellite

Naturally, using this method, the geolocation can be done using one satellite. This method can be further classified into:

1. The geolocation method by a single satellite based on the line of sight (LOS).

   This is a traditional and widely used method [6–10], which locates the transmitters through the intersection between the oriented LOS generated from the two dimensional (2D) direction finding system on the satellite with the earth's surface, as shown in Figure 1.2. The advantage of this method is that it can realize 'instantaneous' geolocation, sometimes called a 'single-pulse geolocation'. However, as the LOS in a 3D space must be determined with the 2D direction finding antenna array or a multiple beam antenna, large numbers of antennas and receivers are, generally speaking, required. In addition, the attitude measurements of the observing satellite, including yaw, pitch, and roll angle, also need to be accurate enough.
2. The geolocation method by a single satellite based on particle kinematic parameters.

   This novel method locates the transmitters by the rate of changing information, such as the frequency of the received signal and/or the time of arrival (TOA), or the phase rate of changing information of a long baseline interferometer (LBI) over a period of time. It draws the relative moving information from kinematic features of the transmitters against the satellite observatory platform. Featured with a payload of small volume, light weight, and low power consumption, it is suitable for a microsatellite or a nanosatellite.

According to the orbit altitude, the geolocation by a single satellite based on the LOS can be classified into three types: geolocation by a single LEO satellite, geolocation by a single HEO satellite, and geolocation by a single satellite on a highly elliptical orbit.

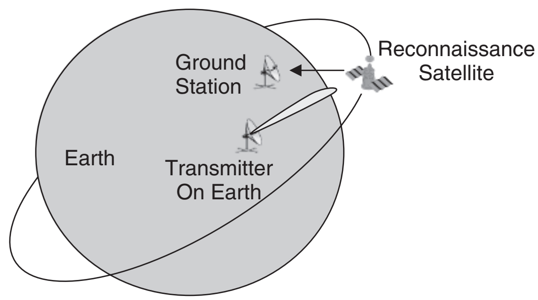

Figure 1.1 Geolocation of an emitter on the earth's surface by a single LEO reconnaissance satellite

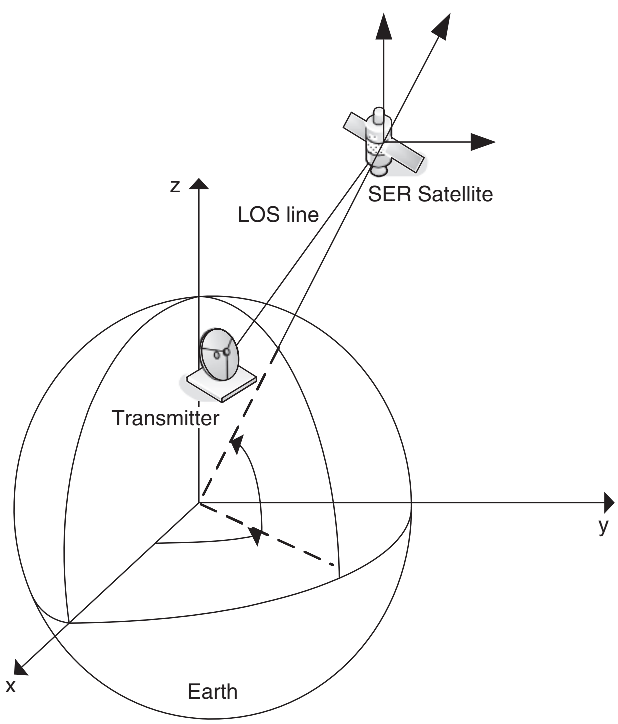

Figure 1.2 The geolocation method used by a single satellite based on the line of sight (LOS)

1. The geolocation by a single LEO satellite

   As the LEO satellite's orbit is low, generally 500–1100 km with an inclination of more than 50°, it is closer to the transmitters on earth compared with the HEO satellites, the signals intercepted by satellites are stronger, and the position can be estimated quite accurately. In addition, its cost is low for production and launching as smaller, low-gain antennas can be applied. Therefore, this was one of first systems developed in history, such as the first ELINT satellites – *Grab* and *Poppy* satellite series of the United States. These satellites can also be applied to monitor the targets on the sea surface through the reconnaissance and geolocation of the radar or communication signal on vessels. The reconnaissance can be run with one satellite or a multiple satellite network. Typical reconnaissance systems are the US *Semos-F* series electronic reconnaissance satellite, the US *White Cloud* series electronic ocean surveillance satellite, and the former USSR *Tselina* series electronic reconnaissance satellite. Its disadvantage is that as the LEO satellite's orbit is low the reconnaissance of the same place cannot be kept for long and the instantaneous coverage field of the satellite may be narrow compared with other orbits.
2. The geolocation method of a single HEO satellite [1–5]

   As the satellite is far away from the transmitters, for example, the altitude of the earth's stationary orbit is approximately 35 800 km, the advantage is that the coverage area is very wide. It can remain stationary over the earth and all-weather, full-time (7/24) monitoring over one area, especially the hotspot ones, can be conducted. In comparison with the LEO satellite, there is no orbit revisit period problem for HEO satellites. They can transmit the reconnaissance data downwards to a ground station for real-time support of tactical operations, which is very meaningful for military strategy and tactics. A typical reconnaissance system is the US *Magnum* series electronic reconnaissance satellite. However, as the emitter on earth is far away from the satellite, the intercepted signals are quite weak. It is necessary to intercept the signals with a large-diameter, high-gain antenna. As a result of the long distance, there is a high demand placed upon direction finding accuracy for geolocation of the emitter on earth, which makes it quite challenging as far as technology is concerned.
3. The geolocation method by a single satellite on a highly elliptical orbit based on direction finding

   The apogee of such a satellite is approximately 38 720 km and perigee is about 400 km with inclination of 63.4°. The satellite is primarily used for the continuous reconnaissance and monitoring of the areas with high altitude. It can conquer the disadvantages of poor reconnaissance performance of a synchronous orbit electronic reconnaissance satellite in such areas. Aypical system is the US *Jump Seat* series electronic reconnaissance satellite.

1.2.1.2 The Geolocation Method Based on TDOA–FDOA of a Dual Satellite

Naturally, with this method, dual satellites are formed in one group for reconnaissance. If the signals from the same transmitters can be intercepted by dual satellites at the same time, the geolocation of the emitter on earth could be achieved after signal processing and location estimation [1–5, 11–16].

Generally speaking, in such a system, two satellites may cooperate with each other and are on a same orbit to measure the signal TDOA and FDOA parameter. The basic principle is: as the distance between the ground emitter and two satellites are different, the signal arrives at two satellites at different times. If the TDOA can be calculated, a hyperboloid of revolution with

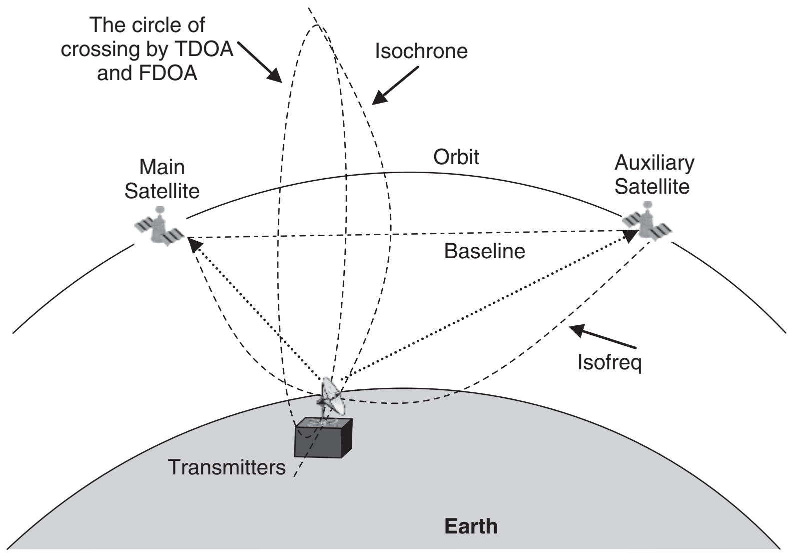

Figure 1.3 The geolocation method by dual satellites

two satellites as the focus can be determined. Additionally, as speed, that is, radial velocity of two satellites, makes a different projection on the line between the transmitter and reconnaissance satellite, the Doppler frequency shift of the intercepted signals will not be the same. Meanwhile, measurement of the FDOA can be applied to determine a constant Doppler difference curve of revolution with two satellites as the focus. Making an intersection between the hyperboloid of revolution based on equal TDOA and equal FDOA curves of revolution, we can get a circle whose axis is the line of the satellites. Then if we make an intersection between the circle and the earth's surface, we will get two positions. Delete the ambiguous one and we can locate the transmitters. This is shown in Figure 1.3.

Because the LEO satellites move fast and the Doppler frequency difference between two satellites is significant, this method is featured as geolocation by short time accumulation and high accuracy for an LEO dual-satellite reconnaissance system. If dual satellites are on the same orbit, the distribution of geolocation is irrelevant with latitude compared with the three-satellite TDOA geolocation system. As the geolocation by the TDOA and FDOA is on the basis of a cross-ambiguity function (CAF) over the length of a certain duration of signals, the geolocation of the multiple signals can also be realized, even if they are at the same frequency and transmitted at a same time. The disadvantage of this method is that there is the poor geolocation accuracy area near to the subsatellite track. It is a result of the geolocation circle formed by the TDOA and FDOA plane and the earth's surface being nearly tangential in the area close to the subsatellite track. In addition, in order to measure the TDOA and FDOA from received signals in the process of geolocation, the correlation between the two signals must be computed and the signal or signal data should be sent to the same place, such as the primary satellite, ground station, or the tracking and data relay satellite system (TDRSS). Thus, it exerts a high demand upon the high-speed satellite-to-satellite data link or satellite-to-land data link, and the synchronization of time and frequency between the satellites. Besides, left or right ambiguity is another issue that should be deal with – it is hard to judge whether the target transmitters are located on the left or the right of a subsatellite track in mathematics, that is, the ambiguous geolocation problem. We have to resort to other technical measures such as direction finding information to solve such a problem. Therefore, technically speaking, it is more complicated to realize the dual-satellite TDOA−FDOA geolocation system compared with a single satellite based on the LOS and geolocation by multiple satellites based on TDOA.

1.2.1.3 Geolocation Method by Multiple Satellites Based on TDOA

This system locates the transmitters by a set of N satellites ($N \geq 3$). Among the multiple satellite geolocation system based on TDOA, the three-satellite geolocation based on TDOA has been discussed in many papers [1–5, 11, 17–21].

This method locates the emitters on the earth's surface by TDOAs of the signals arriving at multiple satellites. The basic theory is that as distances between the emitters on earth and different satellites are different, the times of the transmitted signals arriving at the transmitters are also different. So the TDOA of the intercepted signals at any two satellites from the transmitters can determine a hyperboloid of revolution with two satellites as the focus point. The TDOA of the signals arriving at another two of the satellites from the transmitters can determine another hyperboloid of revolution, with two satellites as the focus. Thus the two hyperboloids of revolution can be intersected by each other to form a curve, which further intersects with the earth's surface to obtain two points, which are generally located at the two sides of the earth. When the ambiguous point is ascertained (because normally the ambiguous point is in the other hemisphere of the earth and the transmitting source cannot be at such a point from *a priori* knowledge), the position of the transmitters on the earth's surface can be located. This process is shown in Figure 1.4.

In the geolocation process of the transmitters, we need the *a priori* information of the transmitters on the earth's surface so that the geolocation is influenced by the altitude error of

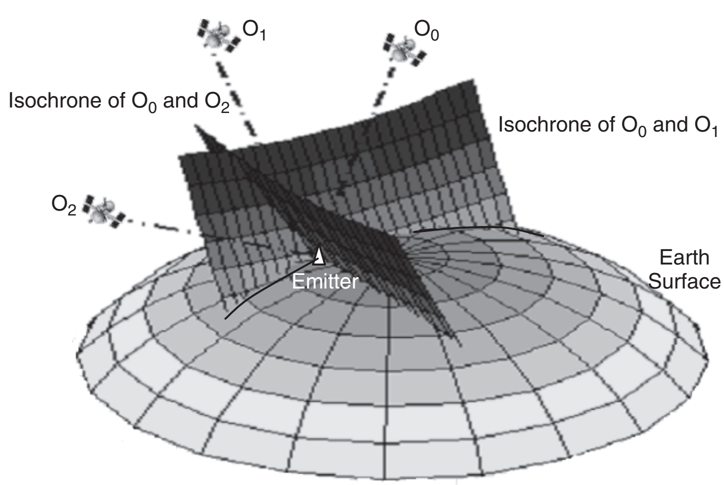

Figure 1.4 Geolocation by three satellites based on TDOA

the transmitters. However, as the altitude of the emitter on an ocean is always approximately zero, the acceptable geolocation accuracy can be achieved. Using this method, surveillance over the transmitters on an ocean can be realized in a very large area (3000–7000 km diameter). An LEO constellation by three to four satellites based on the TDOA is generally formed. For example, in typical TDOA satellites – US first and second generation *White Cloud* series electronic ocean surveillance satellites – the orbit altitude is approximately 1100 km and inclination is about 63°.

This method is featured with relatively simple, high accuracy in large areas as well as the capability of instantaneous geolocation (sometimes called 'single-pulse geolocation'). In the coverage area of multiple satellites, the highest accuracy is near the subsatellite point, which makes it very suitable for the geolocation of strong power pulsing signal sources like radar. The disadvantage is the changing geolocation accuracy within certain ranges and poor performance when three satellites are in an approximate straight line due to the unstable satellite geometry, because satellites are generally not on the same orbit. In addition, there are other problems such as the 'common view' problem of three satellites, which means that multiple satellites should intercept the same pulse, the TDOA ambiguity problem of a high pulse repetition frequency (PRF) radar signal would occur, the matching problem of pulse and the synchronization problem of the time between satellites would interfere, and so on.

1.2.2 Tracking of an Emitter on a Satellite

The geolocation of a satellite emitter refers to tracking of the emitter satellite through the geolocation of its signals by another reconnaissance satellite. As the satellite moves according to certain orbit rules in space, we also call this process an orbit determination process. Its application is wide and it can be classified into two groups: the first application is for the spacecraft space telemetry, tracking, command, and monitoring (TTC&M), which aims at tracking a cooperative satellite; the second application aims at tracking uncooperative satellites through which the electromagnetic surveillance of the space emitters can be achieved and the information of the orbit, status, and function of satellites can be deduced. In this book we will focus on the second group and take the issue of orbit determination of a moving satellite transmitter by a single satellite into consideration.

According to the type of signal, it can be classified into two groups. The first one is the LOS geolocation system, or bearings only tracking system, which is measured by photoelectric sensors such as a camera or infrared imaging sensor. The tracking of the emitter of a satellite can be made through measurement of the emitter's LOS information. The second one is the passive tracking system which intercepts the radio signal transmitted from the emitter. With some parameter estimation and tracking algorithms, the location, speed, or elements of the uncooperative satellite orbit can be identified. The signals intercepted from the satellite are mostly the satellite-to-satellite data-link signals, such as communication, command and control, navigation or telemetry signals. In this way uncooperative orbit determination and tracking can also be achieved.

As shown in Figure 1.5, when signals are sent from the target satellite to the geostationary data relay satellite, such as the TDRSS, with the analysis and parameter estimation of the signals intercepted by a reconnaissance satellite, the location, speed, and elements of orbits of the uncooperative satellite can be estimated.

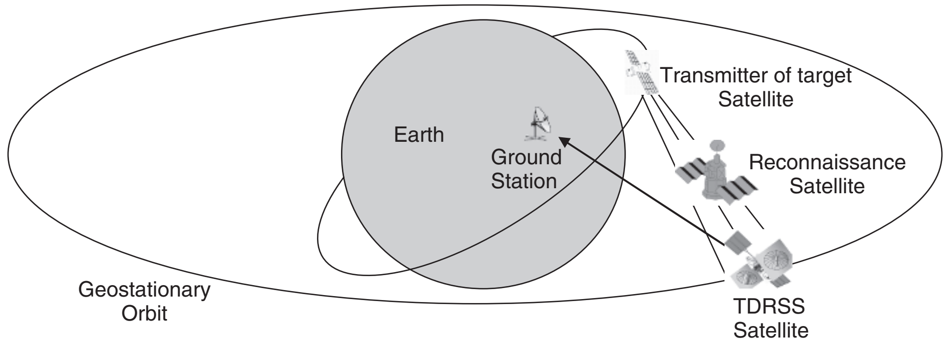

Figure 1.5 Satellite-to-satellite geolocation

With the passive working mode on photoelectric sensors (such as a camera or infrared imaging sensor), only the target's bearings information can be obtained. The bearings or LOS can be measured accurately with an accuracy of approximately $4''-10''$ in some applications. On the other hand, after passively intercepting radio signals, the target's bearing, frequency, and its changing rate may also be measured. The accuracy of these parameters is related to the signal processing algorithms and device technologies. Generally speaking, the latter's accuracy is lower than the accuracy achieved with the former one.

1.2.3 Geolocation by Near-Space Platforms

Near space refers to the space between the highest altitude at which a contemporary airplane can fly and the lowest altitude at which a satellite can fly [22–24]. Currently speaking, aircraft in the near space include a free balloon, airship, unmanned aerial vehicle (UAV), and hypersonic UAV. As the full-time, large-scaled and all-weather electronic surveillance can be conducted over one area, research of this geolocation application is rather useful. The geolocation by a near-space platform can be classified into the geolocation by multiple near-space platforms, such as the geolocation based on TDOA and the geolocation by a single near-space platform based on particle kinematics.

Based on the ground and space emitter, this book introduces various geolocation methods and their theories, methods, analysis, and technologies. We hope it will be beneficial to your understanding of the SER geolocation theory and methods.

1.3 Structure of a Typical SER System

Normally, the electronic reconnaissance satellite consists of the satellite platform and the effective payload. As the carrier of the effective payload, the satellite platform is composed of TTC&M equipment, power, and shell. With reference to the SER satellite, the effective payload refers to the electronic reconnaissance equipment. Its primarily purpose is to intercept, analyze, and store the electromagnetic transmitter signals of the electronic equipment. The

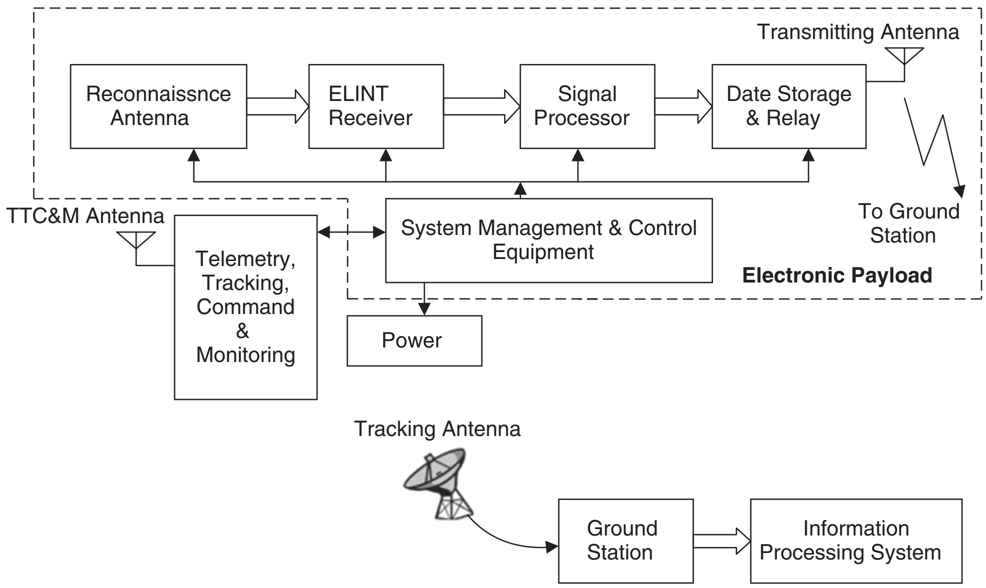

Figure 1.6 Components of the electronic reconnaissance effective payload

effective payload consists of an antenna, receiver, signal processor, system administration and control equipment, and storage and transmittal equipment. For example, the typical structure of an LEO electronic reconnaissance satellite is shown in Figure 1.6.

The functional parts of the effective payload in an SER satellite are listed as follows [25, 26]:

- Reconnaissance antenna

  It receives the intercepted electromagnetic signals with some gain, including radar, communication, and telemetry signals. The type of antenna varies according to the task of the satellite. The narrow-beam scanning antenna, multibeam antenna, phase/amplitude comparison antenna, or phased-array antenna can be used.
- Electronic reconnaissance receiver (ELINT receiver)

  The electronic reconnaissance receiver is also called the electronic intelligence receiver. It is used to magnify, control, and filter the signals in order to extract particular signals. As a result of the high altitude and wide coverage area of the satellite, it is facing a complicated electromagnetic signal environment. In order to intercept different sources simultaneously, the receiver needs to have a wide frequency coverage, high interception probability, high sensitivity, high accuracy, and strong adaptability of different unknown signals.
- Signal processor

  It processes and analyzes parameters the intercepted analog signals from the receiver by changing them into digital signals. As the satellite equipment is strictly limited in volume, weight, and power consumption, the receiver generally performs some simple operations and compares them with those of ground station signal processing, primarily involving recording, storage, or direct transmission.

- Storage and relay equipment
  It stores the signal data and processing results collected on the satellite temporarily and transmits the data to the ground stations when the satellite is near ground stations. It can be classified into satellite-to-ground and satellite-to-satellite types. The former's equipment is used to send the information at the terminal to the satellite earth station, but by the latter the reconnaissance data are transmitted to the ground through the geostationary data relay satellite by the satellite-to-satellite link.
- System control and administration equipment
  It receives directions and commands from the ground and controls the system to operate according to the task mode set by the ground.

References

1. Wang, Y. and Liu, Y. (2003) *Military Satellite and Application Concept*. Beijing: National Defence Industry Press, May 2003 (in Chinese).
2. Lu, Y., Wang, Y., Wu, Z., et al. (2009) *Space Information Confrontation*. Beijing: National Defence Industry Press, January 2009 (in Chinese).
3. Bernard, R.L. (2009) *Electronic Intelligence (ELINT) at NSA*, Center for Cryptologic History National Security Agency.
4. Feng, R. (2000) Development of electronic reconnaissance satellites in America. *Space International*, 6–8 (in Chinese).
5. Chen, M. and Xu, J. (2000) Application and development of modern electronic reconnaissance satellites. *Space International*, 16–18 (in Chinese).
6. Zhang, R. (1998) *The Kinetics and Control of Attitude for Satellite Orbit*. Beijing: Beihang University Press, May 1998 (in Chinese).
7. Liu, H., Liu, Z., Jiang, W., et al. (2009) Fusion algorithm for emitter localization based on satellite carried direction finding system. *System Engineering and Electronics*, **12**(31): 2785–2789 (in Chinese).
8. Gong, W., Feng, D., Xie, K., et al. (2005) Research on the self-calibration approach of satellite carried direction finding localization bias. *Aerospace Electronic Warfare*, **2**(21): 25–30 (in Chinese).
9. Yang, B., Zhang, M., and Li, L. (2009) Algorithm for single-satellite DOA localization based on model WGS284. *Aerospace Electronic Warfare*, 25: 24–26 (in Chinese).
10. Yuan, X. (2005) Research on ground target direction finding localization by remote-sensing satellite. *Space Electronic Technology*, 1–9 (in Chinese).
11. Ho, K.C. and Chan, Y.T. (1997) Geolocation of a known altitude object from TDOA and FDOA measurements. *IEEE Transactions on Aerospace and Electronic Systems*, **33**(3): 770–783.
12. Pattison, T. and Chou, S. I. (2000) Sensitivity analysis of dual-satellite geolocation. *IEEE Transactions on Aerospace and Electronic Systems*, **36**(1): 56–71.
13. Guo, F. (2008) Analysis of dual-satellites TDOA–FDOA passive localization. *Aerospace Electronic Warfare*, **22**: 20–23 (in Chinese).
14. Guo, F. and Fan, Y. (2008) Combined dual-satellite TDOA and FDOA localization and its error analysis. *Journal of Astronautics*, **29**(4): 1381–1386 (in Chinese).
15. Huang, Z. and Lu, J. (2003) Space-based passive localization and modern small satellite technology. *Journal of the Academy of Equipment Command and Technology*, **14**: 24–29.
16. Qu, W., Ye, S., and Sun, Z. (2005) Algorithm of location iteration for satellite interference location. *Journal of Electronics and Information Technology*, **27**(5): 797–800 (in Chinese).
17. Foy, W. H. (1976) Position-location solutions by Taylor-series estimation. *IEEE Transactions on Aerospace and Electronic Systems*, **AES-12**(2): 187–194.

18. Torrieri, D. J. (1984) Statistical theory of passive location systems. *IEEE Transactions on Aerospace and Electronic Systems*, **AES-20**(2): 183–198.
19. Zhong, D. (2002) *Research on Three-Satellite TDOA Geolocation Based on WGS-84*. Changsha: Graduate School of National University of Defense Technology, November 2002 (in Chinese).
20. Zhong, D., Deng, X., and Zhou, Y. (2003) A location method based on WGS-84 earth model using satellite TDOA measurements. PhD Dissertation (in Chinese).
21. Li, J. (2004) Research on four-satellite TDOA location algorithm. *Electronic Information Warfare Technology*, **7**(19): 3–7 (in Chinese).
22. Wang, Y., Li, D., and An, Y. (2009) Application of near-space vehicle in electronic reconnaissance. *Aerospace Electronic Warfare*, **4**(25): 18–24 (in Chinese).
23. Yi, Z. and Li, Q. (2006) Analysis of near-space vehicle and its military application. *Journal of the Academy of Equipment Command and Technology*, **5**(17): 64–69 (in Chinese).
24. Li, Y., Yao, W., Zheng, W., et al. (2006) Type and characteristics of near-space system. *Satellite Application*, **3**(14): 1–6 (in Chinese).
25. Hou, Y., An, W., Guo, F., et al. (2009) *Principles of Electronic Warfare*. Beijing: Publishing House of Electronics Industry, September 2009 (in Chinese).
26. Leopold, C. (1989) *Space-Based Radar Handbook*, Norwood, MA: Artech House.