OPTICAL SYSTEMS

INSTRUMENT	APERTURE (cm)	TIMING ACCURACY (msec)	DIRECTIONAL ACCURACY (arc seconds)	FAINTEST SATELLITE (magnitude)
Baker-Nunn tracking camera	50	0.1	2	12
Hewitt camera	63	0.2	1	7.5
BC-4 camera	12	0.1	2	6
PC-1000 camera	20	0.1	2	6
NAFA 3c/25 camera	10	2	5	4.5
MOTS-40 camera	20	2	2	5
Kinetheodolite photographic	20	10	20	4
Kinetheodolite photovisual	10	10	40	8
70-mm theodolite	7	100	110	8
7 x 50 binoculars	5	100	110	8
11 x 80 binoculars	8	100	70	9.5
20-cm telescope	20	100	70	11

OPTICAL SYSTEMS

Optical systems are those systems which utilize the visible part of the electromagnetic spectrum. This definition would encompass astronomical positioning using a theodolite or sextant and also laser ranging. However, we will not consider these techniques in this section. Conventional astronomical positioning has been discussed in Chapter 1, and laser ranging will be discussed later in this chapter.

Optical systems range in accuracy and complexity from simple binoculars to 60 cm tracking cameras. They have been used in the past for both satellite tracking (i.e., orbit determination) and terrestrial positioning but only the tracking cameras provided geodetically-useful results [Henriksen, 1977]. A tracking camera records a photographic image or a series of images of a satellite, either from a flashing beacon or via reflected sunlight, together with the images of background stars. The time of exposure is also precisely recorded. The positions of the satellite images on the processed film are subsequently measured with respect to stars in the field of view. If the positions of the stars are known, then the topocentric right ascension and declination of the satellite can be determined. Three such determinations combined with the known coordinates of the camera are sufficient for determining the orbit of the satellite. Additional observations can be used to improve the orbit's accuracy.

Alternatively, if the orbit of the satellite is known, it is possible to determine the geocentric coordinates of the camera. Two techniques have been used. In the ***geometric*** method, two or more cameras simultaneously record satellite images and the camera positions are then determined by triangulation. In the ***dynamic*** method, observations are not necessarily synchronized but precise knowledge of the satellite orbit is required. Several three-dimensional networks were established using these techniques [Henriksen, 1977]. One of them was the BC-4 worldwide satellite triangulation network, a network of 45 stations whose coordinates were established through observations of the balloon satellite PAGEOS, using Wild BC-4 cameras. The relative positions of the stations were determined with an estimated accuracy of about 5 m. Greater accuracy in position determination using satellite photography is not readily achievable due to a number of error sources. Chief among these are scintillations of the satellite due to atmospheric turbulence and distortions in the photographic emulsion. Consequently, in geodesy, satellite photography has been superseded by other techniques.

Optical systems are still an important source of information for satellite orbit determination and surveillance. They figure prominently, for example, in the U.S. Air Force's Spacetrack System and its Ground-based Electro-Optical Deep Space Surveillance (GEODSS) System.

EARLY RADIO RANGING AND DIRECTION FINDING SYSTEMS

SYSTEM (Operators)	FREQUENCY (MHz)	OBSERVABLE	ACCURACY Range (m)	ACCURACY Direction (")
C- and S-band radar (U.S. DoD, NASA)	5400-5900 2100-2300	phase	2-5	20
GRARR (Goddard Space Flight Center)	S-band (e.g. 2270 up 1705 down)	phase and phase rate	5	
SECOR (DoD)	420.9 up 449, 224.5 down	phase	3-10	
Minitrack (NASA)	108; 136-138	interferometric phase		20

EARLY RADIO RANGING AND DIRECTION FINDING SYSTEMS

The radio portion of the electromagnetic spectrum also found early use in satellite geodesy. It was the study of the Doppler shift of the radio beacons in the early satellites that led to the first real improvement in the determination of the shape of the earth in over 100 years. Several radio systems were developed for satellite tracking and orbit determination. In the United States, these systems included **C- and S-band radar**, the **Goddard Space Flight Center Range and Range Rate (GRARR) system**, and NASA's **Minitrack system.** In addition to their role in orbit determination, the systems were utilized for tracking camera calibration and directly for geodetic positioning. The U.S. Army's **Sequential Collation of Range (SECOR) system**, on the other hand, was developed specifically for positioning purposes.

The C- and S-band radars are operated by the U.S. Department of Defense and by NASA. Radar pulses directed at a satellite are returned by skin reflection or via a transponder, and the two-way pulse travel time is measured. Range accuracies of 2 to 5 m can be obtained. Radars can also provide angular position to about 20".

The GRARR system relies on a transponder in the satellite to respond to an S-band signal transmitted from an antenna on the ground. Superimposed on the carriers by phase modulation are 6 to 8 frequencies between 8 Hz and 500 kHz. The relative phases of the transmitted and received modulations are used to infer the range to the satellite. The multiple modulation frequencies are used to remove the inherent cycle ambiguity. The phase rate or Doppler shift of the received carrier is also measured. The range accuracy of GRARR is about 5 m.

Minitrack, or more fully Prime Minitrack, was NASA's first tracking system. It consists of a pair of crossed interferometers which measure the relative phase of a nominally 136 (formerly 108) MHz signal transmitted by suitably-equipped satellites as received at the two ends of the interferometer. The same principle is used in the U.S. Naval Space Surveillance System and in very long baseline interferometry (see later in this chapter). With Minitrack, the altitude and azimuth of a satellite can be determined to about 20".

The SECOR system, which was operated between 1962 and 1970, consisted of four ground stations each transmitting modulated signals on 420.9 MHz to a transponder on certain satellites. The transponders returned the signal on 449 and 224.5 MHz. By measuring the relative phase of the transmitted and received 585.533 kHz modulation, the range to the satellite could be determined. An additional three modulation frequencies provided ambiguity resolution. Range accuracies of 3 to 10 m were obtained.