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Navigation Systems

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13.1 Introduction

Navigation is the determination of the position and velocity of the mass center of a moving vehicle. The three components of position and the three components of velocity make up a six-component *state vector* that fully describes the translational motion of the vehicle because the differential equations of motion are of second order. Surveyors now use some of the same sensors as navigators but are achieving higher accuracy as a result of longer periods of observation, a fixed location, and more complex, non-real-time data reduction.

In the usual navigation system, the state vector is derived on-board, displayed to the crew, recorded on-board, and often transmitted to the ground. Navigation information is usually sent to other on-board subsystems; for example, to the waypoint steering, engine control, communication control, and weapon-control computers. Some navigation systems, called *position-location systems*, measure a vehicle's state vector using sensors on the ground or in another vehicle (Section 13.5). These external sensors usually track passive radar returns or a transponder. Position-location systems usually supply information to a dispatch or control center.

The term *guidance* has two meanings, both of which differ from *navigation*:

1. Steering toward a destination of known position from the vehicle's present position, as measured by a navigation system. The steering equations are derived from a plane triangle for nearby destinations and from a spherical triangle for distant destinations.
2. Steering toward a destination without calculating the state vector explicitly. A guided vehicle homes on radio, infrared, or visual emissions. Guidance toward a *moving* target is usually of interest to military tactical missiles in which a steering algorithm assures impact within the maneuver and fuel constraints of the interceptor. Guidance toward a *fixed* target involves beam riding, as in the Instrument Landing System, Section 13.5.

The term *flight control* refers to the deliberate rotation of an aircraft in three-dimensions around its mass center.

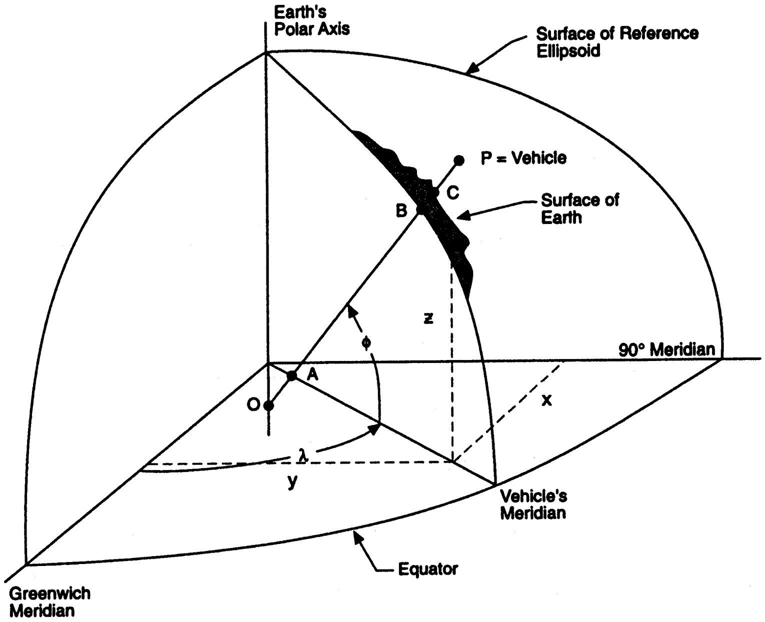

FIGURE 13.1 Latitude–longitude–altitude and x,y,z, coordinate frames. ϕ = geodetic latitude; $\overline{OP}$ is normal to the ellipsoid at B; λ = geodetic longitude; $h = \overline{BP}$ = altitude above the reference ellipsoid = altitude above mean sea level.

13.2 Coordinate Frames

Navigation is with respect to a coordinate frame of the designer's choice. For navigation within a few hundred kilometers (e.g., by helicopter), various map grids exist whose coordinates can be calculated from latitude–longitude (Fig. 13.1). NATO helicopters and land vehicles use a Universal Transverse Mercator grid. Long-range aircraft navigate relative to an earth-bound coordinate frame, the most common of which are latitude–longitude–altitude and rectangular x, y, z (Figure 13.1). Latitude–longitude–altitude coordinates are not suitable in polar regions because longitude is indeterminate. GPS does its calculations in x, y, z and may convert to latitude–longitude–altitude for readout. The most accurate world-wide reference ellipsoid is described in WGS-84, 1991. Spacecraft in orbit around the earth navigate with respect to an earth-centered, inertially nonrotating coordinate frame whose z axis coincides with the polar axis of the earth and whose x axis lies along the equator. Interplanetary spacecraft navigate with respect to a sun-centered, inertially nonrotating coordinate frame whose z axis is perpendicular to the *ecliptic* and whose x axis points to a convenient star (Battin, 1987).

13.3 Categories of Navigation

Navigation systems can be categorized as:

1. *Absolute navigation systems* that measure the state vector without regard to the path traveled by the vehicle in the past. These are of two kinds:
   - Radio systems (Section 13.5). They consist of a network of transmitters (sometimes also receivers) on the ground or in satellites. A vehicle detects the transmissions and computes its position relative to the known positions of the stations in the navigation coordinate frame. The vehicle's velocity is measured from the Doppler shift of the transmissions or from a sequence of position measurements.

- Celestial systems (Section 13.6). They measure the elevation and azimuth of celestial bodies relative to the local level and North. Electronic star sensors are used in special-purpose high-altitude aircraft and in spacecraft. Manual celestial navigation was practiced at sea for millennia (see Bowditch).

2. *Dead-reckoning navigation systems* that derive their state vector from a continuous series of measurements beginning at a known initial position. There are two kinds: those that measure vehicle heading and either speed or acceleration (Section 13.4) and those that measure emissions from continuous-wave radio stations whose signals create ambiguous "**lanes**" (Section 13.5). Dead-reckoning systems must be reinitialized as errors accumulate and if power is lost.
3. *Mapping navigation systems* that observe and recognize images of the ground, profiles of altitude, sequences of turns, or external features (Section 13.7). They compare their observations to a stored database, often on compact disc.

13.4 Dead Reckoning

The simplest dead-reckoning systems measure vehicle heading and speed, resolve speed into the navigation coordinates, then integrate to obtain position (Figure 13.2). The oldest heading sensor is the magnetic compass, a magnetized needle or electrically excited toroidal core (called a *flux* gate), as shown in Figure 13.3. It measures the direction of the earth's magnetic field to an accuracy of 2° at a steady velocity below 60° magnetic latitude. The horizontal component of the magnetic field points toward *magnetic north* or *south*. The angle from true to magnetic north is called *magnetic variation* and is stored in the computers of modern vehicles as a function of position over the region of anticipated travel (Quinn, 1996). *Magnetic deviations* caused by iron and motors in the vehicle can exceed 30° and must be compensated for in the navigation computer, using tables that account for the power-on status of subsystems.

A more complex heading sensor is the *gyrocompass*, consisting of a spinning wheel whose axle is constrained to the horizontal plane (often by a pendulum). The ship's version points north, when properly

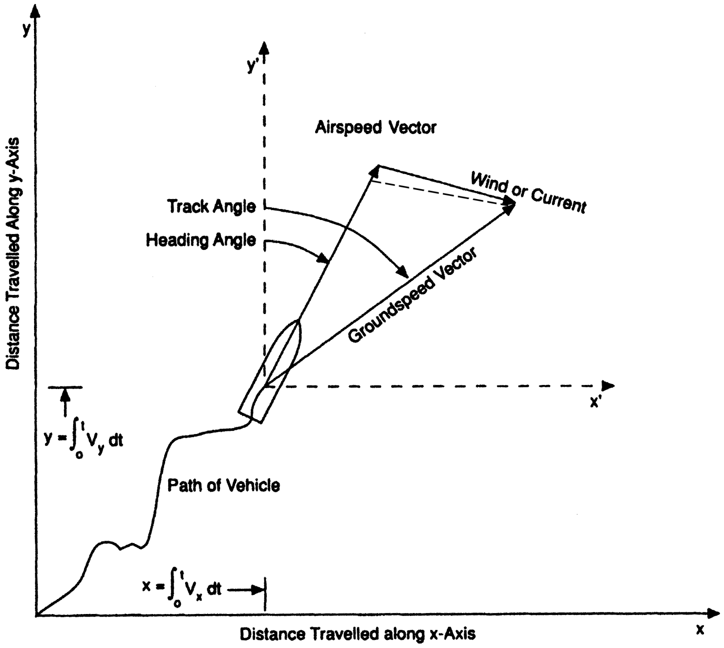

FIGURE 13.2 Geometry of dead reckoning.

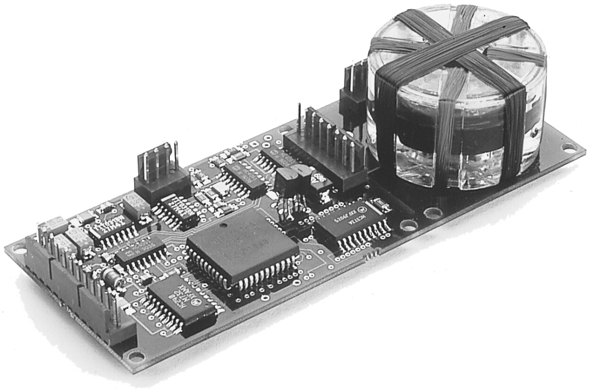

FIGURE 13.3 Saturated core ("flux-gate') magnetometer, mounted on a "compass engine" board. The two orthogonal sensing coils (visible) and the drive coil, wound on the toroidal core, measure two components of the magnetic field in the plane of the toroid. (Courtesy of KVH Industries, Inc.)

compensated for vehicle motion, and exhibits errors less than a degree. The aircraft version (more properly called a *directional gyroscope*) holds any preset heading relative to earth and drifts at 50°/hr or more. Inexpensive gyroscopes (some built on silicon chips as vibrating beams with on-chip signal conditioning) are often coupled to magnetic compasses to reduce maneuver-induced errors and long-term drift.

The usual speed-sensor is a *pitot tube* that measures the dynamic pressure of the air stream from which airspeed is derived in an *air-data* computer. To compute ground speed (Figure 13.2) the velocity of the wind must be vectorially added to that of the vehicle. Hence, unpredicted wind or air current will introduce an error into the dead-reckoning computation. Most sensors are insensitive to the component of airspeed normal to their axis (*drift*). A Doppler radar measures the frequency shift in radar returns from the ground or water below the aircraft, from which speed is measured directly. Multibeam Doppler radars can measure all the components of the vehicle's velocity. Doppler radars are widely used on military helicopters.

The most precise dead-reckoning system is an *inertial navigator* in which accelerometers measure the vehicle's acceleration while gyroscopes measure the orientation of the accelerometers. An on-board computer resolves the accelerations into navigation coordinates and integrates them to obtain velocity and position. The gyroscopes and accelerometers are mounted in either of two ways:

1. Fastened directly to the airframe ("strap-down"), whereupon the sensors are exposed to the maximum angular rates and accelerations of the vehicle. This is the usual inertial navigator in 2000 (Figure 13.4). Attitude is computed by a *quaternion* algorithm (Kayton and Fried, 1997, pp. 352–356) that integrates measured angular rates in three dimensions.
2. On a servo-stabilized platform in gimbals that angularly isolate them from rotations of the vehicle. In 2000, gimballed navigators are used only on specialized, high-accuracy military aircraft. They measure attitude directly from the gimbal angles. Their instruments are in a benign angular-environment and held at a constant orientation relative to gravity.

Inertial-quality gyroscopes measure vehicle orientation within 0.1° for steering and pointing. Most accelerometers consist of a gram-sized proof-mass mounted on flexure pivots. The newest accelerometers have proof masses that are etched into silicon chips. Older gyroscopes contained metal wheels rotating in ball bearings or gas bearings. More recent gyroscopes contain rotating, vibrating rings whose frequency of oscillation measures angular rates. The newest gyroscopes are evacuated cavities or optical fibers in which counter-rotating laser beams are compared in phase to measure the sensor's angular velocity relative

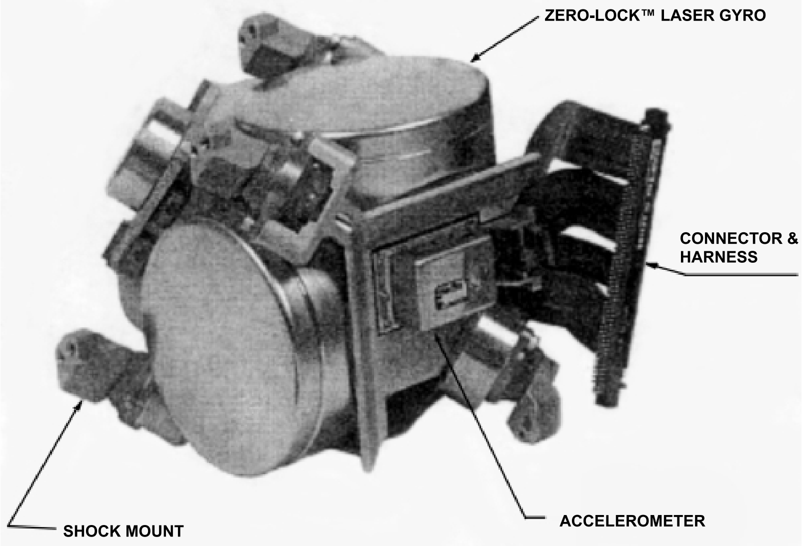

FIGURE 13.4 Inertial reference unit. Two laser gyroscopes (flat discs), an accelerometer, an electrical connector, and four shock mounts are visible. This unit is used in Airbuses and many military aircraft such as the F-18 and Comanche helicopter. (Courtesy of Litton Guidance and Control Systems.)

to *inertial space* about an axis normal to the plane of the beams. Vibrating hemispheres and rotating vibrating tines are the basis of some navigation-quality gyroscopes (drift rates less than 0.1 deg/h).

Fault-tolerant configurations of cleverly oriented redundant gyroscopes and accelerometers (typically four to six) detect and correct sensor failures. Inertial navigators are used aboard airliners, in most military fixed-wing aircraft, in space boosters and entry vehicles, and in manned spacecraft.

13.5 Radio Navigation

Scores of radio navigation aids have been invented and many of them have been widely deployed, as summarized in Table 13.1.

The most precise is the global positioning system (GPS), a network of 24 satellites and a half-dozen ground stations for monitoring and control. A vehicle derives its three-dimensional position and velocity from ranging signals at 1.575 GHz received from four or more satellites (U.S. military users also receive 1.227 GHz). The one-way ranging measurements depend on precise atomic clocks on the spacecraft (one part in 10E13) and on precise clocks on the aircraft (one part in 10E8) that can be calibrated to behave briefly as atomic clocks by taking redundant range measurements from satellites. The former Soviet Union deployed a similar system, called GLONASS. GPS offers better than 30-m ranging errors to civil users and 10-m ranging errors to military users. Simple receivers were available for less than $100 in 2000. GPS provides continuous worldwide navigation for the first time in history. It will make dead reckoning unnecessary on many aircraft and will reduce the cost of most navigation systems. Figure 13.5 is an artist's drawing of a GPS Block 2F spacecraft, scheduled for launch in the year 2005.

Differential GPS (DGPS) employs one or more ground stations at known locations, which receive GPS signals and transmit measured errors on a radio link to nearby ships and aircraft. DGPS improves accuracy (centimeters for fixed observers) and detects faults in GPS satellites. In the late 1990s, the United States was conducting experiments with a nationwide DGPS system of 25 to 50 ground stations. This *Wide Area Augmentation System* (WAAS) could eventually replace VORTAC (below) and Category I ILS. A denser network of DGPS stations and GPS-emulating *pseudolites*, whose stations are located at airports,

TABLE 13.1 Worldwide Radio Navigation Aids for Aviation

System	Frequency Hz	Frequency Band	Number of Stations	Number of Aeronautical Users
Loran-C/Chaika	100 kHz	LF	50	120,000
Beacon*	200–1600 kHz	MF	4000	130,000
Instrument Landing System (ILS)*	108–112 MHz 329–335 MHz	VHF UHF	1500	150,000
VOR*	108–118 MHz	VHF	1500	180,000
SARSAT/COSPAS	121.5 MHz 243,406 MHz	VHF UHF	5 satellites	200,000
JTIDS	960–1213 MHz	L	None	500
DME*	962–1213 MHz	L	1500	90,000
Tacan*	962–1213 MHz	L	850	15,000
Secondary Surveillance Radar (SSR)*	1030, 1090 MHz	L	800	250,000
GPS-GLONASS	1227, 1575 MHz	L	24 + 24 satellites	120,000
Radar Altimeter	4200 MHz	C	None	20,000
MLS*	5031–5091 MHz	C	50	100
Weather/map radar	10 GHz	X	None	10,000
Airborne Doppler radar	13–16 GHz	Ku	None	20,000
SPN-41 carrier-landing monitor	15 GHz	Ku	25	1600
SPN-42/46 carrier-landing radar	33 GHz	Ka	25	1600

*Standardized by International Civil Aviation Organization.

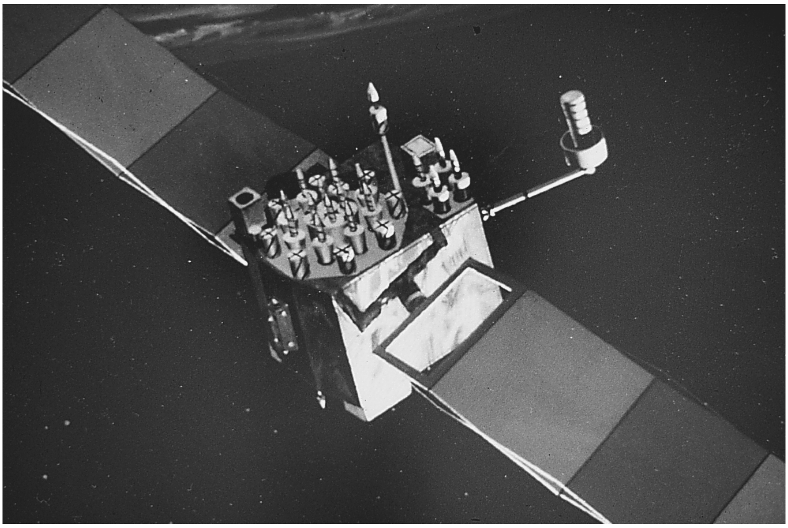

FIGURE 13.5 Global positioning satellite, Block 2F. L-band phased array and S-band control antennas are visible Steerable solar panels power the Spacecraft. Orbit altitude is 10,900 nmi at a 12-hour period. (Courtesy of Rockwell.)

might replace Category II and III ILS and MLS (below). In 2000, the cost, accuracy, and reliability of such a *Local Area Augmentation System* (LAAS) were still being compared with existing landing aids.

Loran is used by general aviation aircraft for en-route navigation and for nonprecision approaches to airports (in which the cloud bottoms are more than 200 feet above the runway; see Table 13.1). The 100-kHz signals are usable within 1000 nautical miles of a “chain” consisting of three or four stations. Chains cover the United States, parts of western Europe, Japan, Saudi Arabia, and a few other areas. The former Soviet Union has a compatible system called Chaika. The vehicle-borne receiver measures the difference in time of arrival of pulses emitted by two stations, thus locating the vehicle on one branch of a hyperbola (Kayton and Fried, 1997, Chapter 4.5.1). Two or more station pairs give a two-dimensional position fix at the intersection of the hyperbolas, whose typical accuracy is 0.25 nmi, limited by propagation uncertainties over the terrain between the transmitting station and the user. The measurement of 100-microsecond time differences is possible with low quality clocks (one part in 10,000) in the vehicles. Loran stations are being upgraded in 2000 so service is assured for the first decade of the third millennium. Loran will be a coarse monitor of GPS and a stand-alone navigation aid whenever GPS is deliberately taken out of service by the U.S. military. These functions may, alternatively, be provided by European or Russian navigation satellites or by private nav-com satellites. These satellite-based supplements to GPS are more accurate than Loran but are subject to the same outages as GPS: solar flares and jammers, for example.

The most widely used aircraft radio aid is VORTAC, whose stations offer three services:

1. Analog bearing measurements at 108 to 118 MHz (called VOR). The vehicle compares the phases of a rotating cardioid pattern and an omnidirectional sinusoid emitted by the ground station.
2. Pulse distance measurements (DME) at 1 GHz. The time delay for an aircraft to interrogate a VORTAC station and receive a reply is measured.
3. Tacan bearing information conveyed in the amplitude modulation of the DME replies from the VORTAC stations.

On short over-ocean flights, the inertially derived state vector drifts 1 to 2 nmi per hour. When an aircraft approaches shore, the VORTAC network updates the inertial state vector and navigation continues to the destination using VORTAC. On long over-ocean flights (e.g., trans-Pacific or polar), GPS can be used alone but is usually used with one or more inertial navigators to protect against failures.

Landing guidance throughout the western world, and increasingly in China, India, and the former Soviet Union, is with the Instrument Landing System (ILS). Transmitters adjacent to the runway create a horizontal guidance signal near 110 MHz and a vertical guidance signal near 330 MHz. Both signals are modulated such that the nulls intersect along a line in space 2.7° above the horizontal, that leads an aircraft from a distance of about 15 nmi to 50 ft above the runway. ILS gives no information about where the aircraft is located along the beam except at two or three vertical *marker beacons*. Most ILS installations are certified to the International Civil Aviation Organization's (ICAO) *Category I*, where the pilot must abort the landing if the runway is not visible at an altitude of 200 ft. Fewer than two hundred ILSs (in 2000) were certified to *Category II*, which allows the aircraft to descend to 100 ft before aborting for lack of visibility. *Category III* allows an aircraft to land at still lower weather ceilings. Category III landing aids are of special interest in western Europe, which has the worst flying weather in the developed world. Category III ILS detects its own failures and switches to a redundant channel within one second to protect aircraft that have failure while flaring-out (within 50 ft of the runway) and can no longer execute a missed approach. Once above the runway, the aircraft's bottom-mounted radar altimeter measures altitude and either the electronics or the pilot guides the flare maneuver. Landing aids are described by Kayton and Fried (1997).

Throughout the western world, civil aircraft use VOR/DME whereas military aircraft use Tacan/DME for en-route navigation. In the 1990s, China and the Commonwealth of Independent States (CIS) were installing ICAO-standard navigation aids (VOR, DME, ILS) at their international airports and along the corridors that lead to them from the borders. Overflying western aircraft navigate inertially or with GPS. Domestic flights within the CIS depended on radar tracking, nondirectional beacons, and an L-band range-angle system called *RSBN*.

It is likely that LAAS will replace or supplement ILS, which has been guaranteed to remain in service at least until the year 2010 (Federal Radionavigation Plan). The U.S. Air Force and NATO may use MLS or LAAS as a portable landing aid for tactical airstrips.

Position-location systems monitor the state vectors of many vehicles and usually display the data in a control room or dispatch center. The aeronautical bureaucracy calls them *Automatic Dependent Surveillance* (ADS) systems. Some vechicles broadcast on-board-derived position. Others derive their state vector from the ranging modulations. Table 13.1 lists *Secondary Surveillance Radars* that receive coded replies from aircraft so they can be identified by human controllers and by collision-avoidance algorithms.

A worldwide network of SARSAT-COSPAS stations monitors signals from satellite-based transponders listening on 121.5, 243, and 406 MHz, the three international distress frequencies. Software at the listening stations calculates the position of Emergency Location Transmitters carried by ships and aircraft to an accuracy of 5 to 15 km at 406 MHz or 15 to 35 km at 21.5 and 243 MHz, based on the observed Doppler-shift history. Thousands of lives have been saved world-wide, from arctic bush-pilots to tropical fishermen.

13.6 Celestial Navigation

Human navigators use sextants to measure the elevation angle of celestial bodies above the visible horizon. The peak elevation angle occurs at local noon or midnight:

$$\text{elev angle (degrees)} = 90 - \text{latitude} + \text{declination}$$

Thus at local noon or midnight, latitude can be calculated by simple arithmetic. When time became measurable at sea, with a chronometer in the 19th century and by radio in the 20th century, off-meridian observations of the elevation of two or more celestial bodies were possible at any known time of night (cloud cover permitting). These fixes were hand-calculated using logarithms, then plotted on charts. In the 1930s, hand-held sextants were built that measured the elevation of celestial bodies from an aircraft using a bubble-level reference instead of the horizon. The accuracy of celestial fixes was 3–20 miles at sea and 5–50 miles in the air, limited by the uncertainty in the horizon and the inability to make precise angular measurements on a pitching, rolling vehicle. Kayton (1990) reviews the history of celestial navigation at sea and in the air.

The first automatic star trackers were built in the late 1950s. They measured the azimuth and elevation of stars relative to a gyroscopically stabilized platform. Approximate position estimates by dead reckoning allowed the telescope to point within a fraction of a degree of the desired star. Thus, a narrow field-of-view was possible, permitting the telescope and photodetector to track stars in the daytime. An on-board computer stored the right ascension and declination of 20 to 100 stars and computed the vehicle's position. Automatic star trackers are used in long-range military aircraft and on space shuttles in conjunction with inertial navigators. Clever design of the optics and of stellar-inertial signal-processing filters achieves accuracies better than 500 ft (Kayton and Fried, 1997).

13.7 Map-Matching Navigation

As computer power grows, map-matching navigation is becoming more important. On aircraft, mapping radars and optical sensors present a visual image of the terrain to the crew. Since the 1960s, automatic map-matchers have been built that correlate the observed image to stored images, choosing the closest match to update the dead-reckoned state vector. Aircraft and cruise missiles measure the vertical profile of the terrain below the vehicle and match it to a stored profile. Matching profiles over distinctive patches of terrain, perhaps hourly, reduces the long-term drift of their inertial navigators. The profile of the terrain is measured by subtracting the readings of a baro-inertial altimeter (calibrated for altitude above sea level) and a radar altimeter (measuring terrain clearance). An on-board computer calculates the autocorrelation function between the measured profile and each of many stored profiles on possible parallel paths of the vehicle. The on-board inertial navigator usually contains a digital filter that corrects the drift of the azimuth gyroscope as a sequence of fixes is obtained. Hence the direction of flight through the stored map is known, saving the considerable computation time that would be needed to correlate for an unknown azimuth of the flight path.

The most complex mapping systems observe their surroundings, by radar or digitized video, and create their own map of the surrounding terrain. Guidance software then steers the vehicle. Optical map-matchers may be used for landings at fields that are not equipped with electronic aids.

13.8 Navigation Software

Navigation software is sometimes embedded in a central processor with other avionic-system software, sometimes confined to one or more navigation computers. The navigation software contains algorithms and data that process the measurements made by each sensor (e.g., inertial or air data). It contains calibration constants, initialization sequences, self-test algorithms, reasonability tests, and alternative algorithms for periods when sensors have failed or are not receiving information. In the simplest systems, a state vector is calculated independently from each sensor while the navigation software calculates the best estimate. Prior to 1970, the best estimate was calculated from a least squares algorithm with constant weighting functions or from a frequency-domain filter with constant coefficients. Now, a *Kalman filter* calculates the best estimate from mathematical models of the dynamics of each sensor (Kayton and Fried, 1997, Chapter 3).

Digital maps, often stored on compact disc, are carried on some aircraft and land vehicles. Terrain is displayed to the crew. Military aircraft add cultural features, hostile radar and missile functions, then superimpose their navigated position. This allows the aircraft to penetrate and escape from enemy territory. Civil operators had not significantly invested in digital databases as of 2000. Algorithms for waypoint steering and for control of the vehicle's attitude are contained in the software of the *flight management* and *flight control* subsystems.

13.9 Design Trade-Offs

The designers of a navigation system conduct trade-offs for each vehicle to determine which navigation systems to use. Tradeoffs consider the following attributes:

- *Cost*, including the construction and maintenance of transmitter stations and the purchase of on-board electronics and software. Users are concerned only with the costs of on-board hardware and software.
- *Accuracy* of position and velocity, which is specified as a circular error probable (CEP, in meters or nautical miles). The maximum allowable CEP is often based on the calculated risk of collision on a typical mission.
- *Autonomy*, the extent to which the vehicle determines its own position and velocity without external aids. Autonomy is important to certain military vehicles and to civil vehicles operating in areas of inadequate radio-navigation coverage. Classes of autonomy are described in Kayton and Fried (1997, p. 10).
- *Time delay* in calculating position and velocity, caused by computational and sensor delays.
- *Geographic coverage*. Radio systems operating below 100 kHz can be received beyond line of sight on earth; those operating above 100 MHz are confined to line of sight. On other planets, new navigation aids—perhaps navigation satellites or ground stations—will be installed,
- *Automation*. The vehicle's operator (on-board crew or ground controller) receives a direct reading of position, velocity, and equipment status, usually without human intervention. The navigator's crew station disappeared in aircraft in the 1970s. Human navigators were becoming scarce, even on ships, in the 1990s, because electronic equipment automatically selects stations, calculates waypoint steering, and accommodates failures.

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Further Information

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