Module 12

Modern Navigation Systems

Inertial Navigation, Doppler, and Atomic Clocks

Module 12C

Doppler systems

Summary of Module 12

- The Keplerian equations from earlier modules are re-examined in terms of conservation of angular momentum, thus yielding expressions for the acceleration versus time of moving bodies. The Schuler frequency is introduced and analyzed in the context of a feedback control system, using as an example problem the inertial navigation of an aircraft flying from Dulles Airport to Beijing. Angular momentum is then re-examined in the context of circus acrobatic performances. (12A)
- Sensors that can measure these accelerations are explored, including mechanical gyroscopes based on rotating flywheels, mechanical gyroscopes that use micro-electrical mechanical devices (MEMs), and optical gyroscopes that exploit the relativistic Sagnac effect (e.g., the ring-laser gyroscope). (12B)
- **Doppler techniques are introduced using the Cospas-SarSat system as a prototypical example. Students will watch a video that describes Cospas-Sarsat in detail. (12C)**
- Atomic clocks and the Allan variance are introduced. A chip-scale atomic clock is described. (12D)
- Students will begin submitting and/or presenting their final projects. (12E)

Reading and Video

- Read about Doppler systems in the primary text (Kayton and Fried, chapter 10 and throughout the text; consult the index)
- Visit Cospas-Sarsat.int to learn more about the Cospas-Sarsat system
- Watch the Cospas-Sarsat video that is posted to the Module 12 site.

The Doppler effect

The Doppler Effect Operation of a Doppler radar is based on the Doppler effect which was predicted in 1842 by the Austrian scientist Christian Doppler in connection with sound waves and was later found also to be exhibited by electromagnetic waves. The Doppler effect can be described as the change in observed frequency when there is relative motion between a transmitter and a receiver. Furthermore, this change in frequency, called the *Doppler shift*, is directly proportional to the relative speed between transmitter and receiver. In the case of electromagnetic waves (unlike the case of sound waves), it makes no difference in the proportionality relationship whether the transmitter, the receiver, or both, are moving. If the relative velocity of the transmitter and receiver is much smaller than the speed of light (as in the case of aircraft), the Doppler shift is expressed by

$$\nu = \frac{V_R f}{c} = \frac{V_R}{\lambda} \tag{10.1}$$

From the primary text, chap. 10

From the text by Kayton & Fried…

To measure the aircraft's velocity, a radar transmitter-receiver is mounted on the aircraft and radiates electromagnetic energy toward the Earth's surface by means of several beams, one of which is shown in Figure 10.2. Some of the energy is backscattered by the Earth and is received by the radar receiver on the aircraft. If the aircraft is moving with a total velocity V, the beam measures V_R:

$$V_R = 2V \cos \gamma = 2V\mathbf{b} \qquad (10.2)$$

where γ is the angle between the direction of the velocity vector V and the direction of the beam centroid, and $\mathbf{b}$ is the unit vector along the beam centroid. V_R is the component of relative aircraft velocity along the beam centroid. The factor 2 appears in Equation 10.2, since both the transmitter and the receiver are moving with respect to the Earth, from which the energy is backscattered. When Equation 10.2 is substituted into Equation 10.1, the following expression results:

$$\nu = \frac{2Vf}{c} \cos \gamma = \frac{2V}{\lambda} \cos \gamma \qquad (10.3)$$

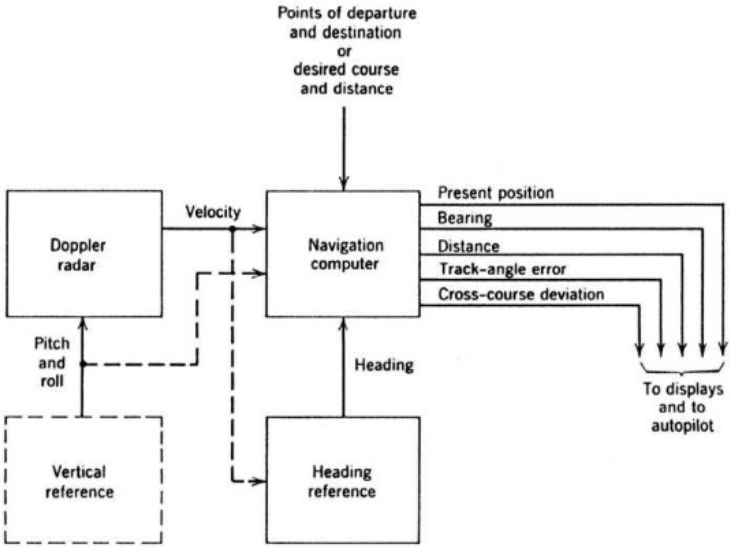


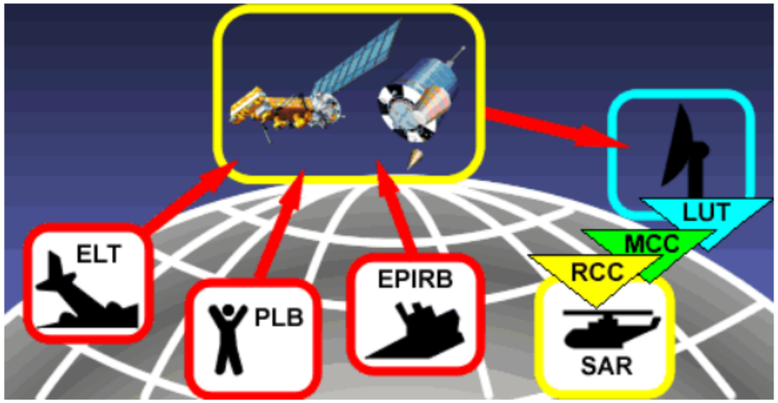
Figure 10.1 Doppler navigation system.

Cospas-Sarsat, from cospas-sarsat.int

Cospas-Sarsat System

Print Email

The basic Cospas-Sarsat concept is illustrated in the adjacent figure. The System is composed of:



- distress radiobeacons (ELTs for aviation use, EPIRBs for maritime use, and PLBs for personal use) which transmit signals during distress situations;
- instruments on board satellites in geostationary and low-altitude Earth orbits which detect the signals transmitted by distress radiobeacons;
- ground receiving stations, referred to as Local Users Terminals (LUTs), which receive and process the satellite downlink signal to generate distress alerts; and
- Mission Control Centers (MCCs) which receive alerts produced by LUTs and forward them to Rescue Coordination Centers (RCCs), Search and Rescue Points Of Contacts (SPOCs) or other MCCs.

The Cospas-Sarsat System includes two types of satellites:

- satellites in low-altitude Earth orbit (LEO) which form the LEOSAR System
- satellites in geostationary Earth orbit (GEO) which form the GEOSAR System

The future Cospas-Sarsat System will include a new type of satellite in the medium-altitude Earth orbit (MEO) which will form the MEOSAR System.

Cospas-Sarsat

- Cospas-Sarsat uses satellites to receive signals from radio beacons operating at 406.1 MHz
- These replace the emergency locator transmitters (ELTs) that operate at 121.5 MHz

Types of C-S beacons

- Emergency Position Indicating Radio Beacons (EPIRBs) are used on ships and commercial aircraft
- Personal Locator Beacons (PLBs) are used by individuals

Cospas-Sarsat.int

- The Cospas-Sarsat web page includes extremely detailed technical information about the system
- Note that the role of Doppler processing has decreased as GPS is incorporated into newer EPIRBs and PLBs.
- But, the use of Doppler by Cospas-Sarsat is an extremely informative paradigm for the use of Doppler in radars, radar altimeters, and other nagivation devices

Cospas-Sarsat Beacons and the LEOSAR System

406-MHz Beacons

Frequencies in the 406.0 - 406.1 MHz band have been exclusively reserved for distress beacons operating with satellite systems. The Cospas-Sarsat 406-MHz beacons have been specifically designed for use with the LEOSAR system to provide improved performance in comparison to the now obsolete 121.5-MHz beacons. 406-MHz beacons have specific requirements on the stability of the transmitted frequency, and the inclusion of a digital message which allows the transmission of encoded data such as unique beacon identification.

Second-generation 406-MHz beacons were introduced in 1997 which allow the transmission in the 406-MHz message of encoded position data acquired by the beacons from global satellite navigation systems such as GPS, using internal or external navigation receivers. This feature is of particular interest for GEOSAR alerts which otherwise would not be able to provide position information.

LEOSAR System

The Cospas-Sarsat LEOSAR system uses polar-orbiting satellites and, therefore, operates with basic constraints which result from non-continuous coverage provided by LEOSAR satellites. The use of low-altitude orbiting satellites provides for a strong Doppler effect in the up-link signal thereby enabling the use of Doppler positioning techniques. The LEOSAR system operates in two coverage modes, namely local and global coverage.

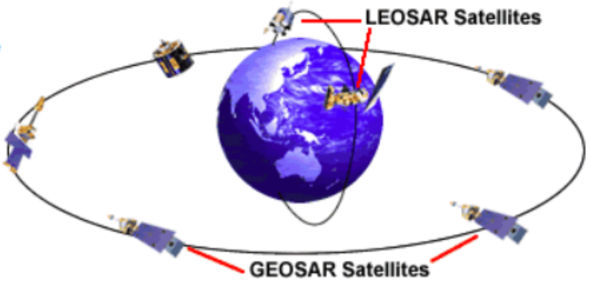
GEOSAR versus LEOSAR

Since GEOSAR satellites remain fixed relative to the Earth, there is no Doppler effect on the received frequency and, therefore, the Doppler positioning technique cannot be used to locate distress beacons. To provide rescuers with position information, the beacon location must be either:

- acquired by the beacon though an internal or an external navigation receiver and encoded in the beacon message, or
- derived from the LEOSAR system Doppler processing.

Cospas-Sarsat has demonstrated that the GEOSAR and LEOSAR system search and rescue capabilities are complementary. For example, the GEOSAR system can provide almost immediate alerting in the footprint of the GEOSAR satellite, whereas the LEOSAR system:

- provides excellent coverage of the polar regions (which are beyond the coverage of geostationary satellites);
- can calculate the location of distress events using Doppler processing techniques; and
- is less susceptible to obstructions which may block a beacon signal in a given direction because the satellite is continuously moving with respect to the beacon.



SAR means search and rescue; LEO is low earth orbit, GEO is geostationary orbit.

MEOSAR

- Cospas-Sarsat payloads will be included onboard the GPS BLK III satellites that will eventually replace existing GPS satellites as they near their end-of-life
- Since GPS satellites orbit in medium earth orbit (i.e., MEOSAR), and because there are so many of them, they confer the advantages of LEOSAR (autonomous position determination of a beacon that isn't GPS equipped) and GEOSAR (instantaneous reception and processing of a distress message).
- The implementation of MEOSAR in the United States is called the Distress Alert Satellite System, or DASS.
    - o DASS is being developed by NASA in cooperation with the Department of Commerce.

Example of the SARSAT weekly rescues report

SARSAT Weekly Rescues Report for the US Search and Rescue Region Apr. 10-17, 2015.

National Oceanic and Atmospheric Administration (NOAA) Search and Rescue Satellite Aided Tracking System Rescues (SARSAT): 4

On 09 April 2015 at 2055 UTC the COSPAS-SARSAT system detected a 406 MHz Personal Locator Beacon (PLB) at 33 47.5N, 077 14.8W, approximately 40 miles east of Bald Head Island, NC. The PLB was activated by the captain of the pleasure craft *Siren Song* when the craft's engine became disabled. The United States Coast Guard District 05 received the SARSAT alert and issued an Urgent Marine Information Broadcast (UMIB). As a result of the UMIB, the Coast Guard was able to establish communications with the vessel. A commercial towing vessel safely towed the disabled craft to port.

1 SARSAT RESCUE

Weekly rescue report, cont'd

On 11 April 2015 at 1439 UTC the COSPAS-SARSAT system detected a 406 MHz Emergency Position-Indicating Radio Beacon (EPIRB) at 29 05.1N, 84 53.6W, 68 NM southeast of Panama City, FL. The EPIRB was manually activated when a 50-Ft Commercial Fishing Vessel *Bandito* became disabled. Coast Guard District 8 received the SARSAT alert and contacted Sector Mobile (SM) to issue an Urgent Marine Information Broadcast. SM made contact with Towing Vessel *Jason E. Duttinger* which was approximately 10 NM south of the SARSAT position. They agreed to change course and assist. When the *Jason E. Duttinger* arrived on scene they confirmed there was a disabled vessel (fishing vessel *Bandito*) but it was not in immediate distress. The owner of the *Bandito* hired Seatow to tow the vessel back into port. Towing Vessel *Jason E Duttinger* remained on scene to act as a communications relay for SM until Seatow arrived.

2 SARSAT RESCUES

Weekly rescue report, cont'd

On 14 April 2015 at 0512 UTC the COSPAS-SARSAT system detected a 406 MHz Personal Locator Beacon (PLB) at 70 50.1N, 159 24.8W, about 2 NM west of Peard Bay in North Slope, AK. The PLB was activated by an individual when his snow-machine broke down. The Alaska Rescue Coordination Center received the SARSAT alert and contacted the North Slope Borough Search and Rescue which dispatched a ground team from Wainwright to the SARSAT position. The ground team located and assisted the individual in distress.

1 SARSAT RESCUE

Total number of rescues for FY 15: 122
Total number of rescues for CY 15: 053

LTJG Jason P. Wilson, 301-817-4757
http://www.nesdis.noaa.gov/sarsat_rescues_2015.html

History of ELTs and Cospas-Sarsat

ELTs were mandated for use on aircraft by Congress after the disappearance of Hale Boggs, the husband of Lindsay Boggs and father of correspondent Cokie Roberts.

Thomas Hale Boggs, Sr. (born February 15, 1914; presumed to have died on October 16, 1972 but not declared dead until January 3, 1973) was an American Democratic politician and a member of the U.S. House of Representatives from New Orleans, Louisiana. He was the House majority leader and a member of the Warren Commission.

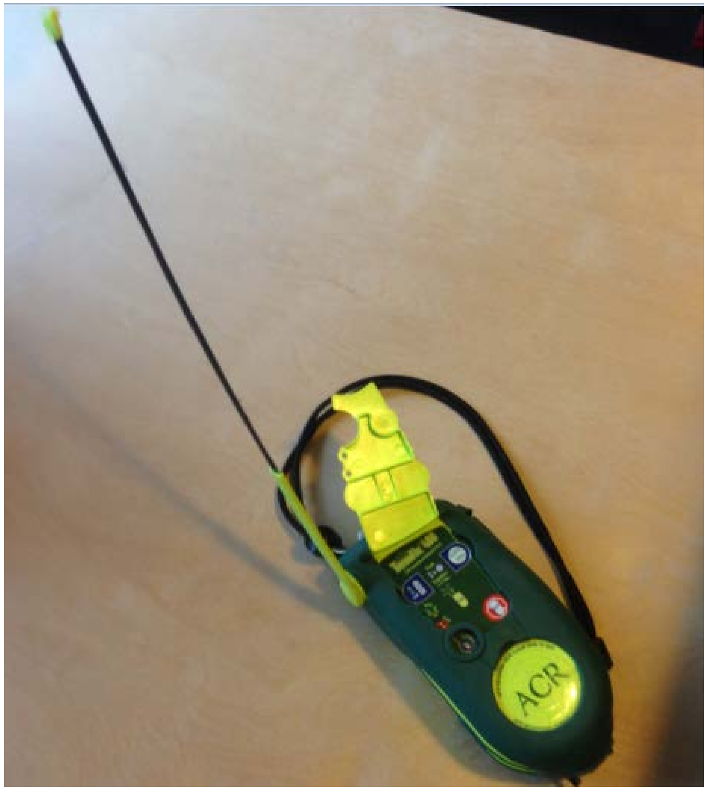
In 1972, while he was still Majority Leader, the twin engine airplane in which Boggs was traveling disappeared over a remote section of Alaska. The airplane presumably crashed and was never found. Congressman Nick Begich, of Alaska, was also presumed killed in the same accident.

From Wikipedia

Failure of ELTs

- 95% of ELT transmissions are false alarms due to inadvertent energizing of impact sensors on ELT transmitters
- 406.1 beacons are a response to the inadequacies of the ELT system
- An aircraft was almost shot down over Washington DC post-9/11 due to a combination of a navigation mishap and interference on 121.5 MHz from an inadvertently transmitting ELT.

A GPS-equipped 406.1 MHz PLB



This device floats and is waterproof

Assignment 12-3

1. Read online about Hale and Lindy Boggs. Do you think the wreckage of the involved aircraft will ever be found?
2. Find and read about the rescue of Abby Sunderland. Who do you think should have paid for the rescue?
3. Track down details of the civil aviation incident over Washington DC that involved an inadvertently transmitting ELT. Comment on how a design deficiency in a deployed system can lead to a mishap decades later.

End of Mod 12C