N63-15999

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APPLICATION OF THE DOPPLER PRINCIPLE TO ROCKETRY

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23.1 The Doppler Effect

The frequency shift due to relative motion was first measured by Christian Doppler at Prague in 1842. In this experiment, the sound from a moving bell was compared with that of a stationary tuning fork. The sound arrived at a higher pitch than that of the tuning fork when the bell was moved rapidly toward the observer and a lower pitch when the bell was moved in the opposite direction. Similar results were obtained when the observer moved while the bell remained stationary. It was later shown that Doppler's principle is applicable to light and radio waves as well as to sound waves.

In the simplest application of this principle to modern tracking problems, the bell is replaced by a crystal-controlled transmitter in the moving vehicle and the frequency of the signal received at a ground station is compared with that of a crystal reference oscillator. The difference is directly proportional to the rate of change of distance between the vehicle and the station. Such measurements are limited in accuracy by the fact that two crystals cannot be ground to exactly the same frequency. In spite of this limitation, however, the system is frequently used when weight limitations preclude the use of more complicated on-board equipment.

The accuracy of the measurement can be greatly increased by the use of an on-board transponder that receives a signal from a ground transmitter and reradiates it to a ground receiver. The return signal, which has been subjected to a Doppler shift on the way up to the vehicle and again on the way down, is then compared with a sample of the original signal from the ground transmitter. The difference is proportional to the loop velocity or the rate of change of the loop distance from the transmitter to the vehicle and back to the receiver. For the special case in which the vehicle is known to be traveling directly away from the ground transmitter and receiver, the velocity of the vehicle is half the loop velocity.

23.2 Philosophy of Doppler Tracking Systems

An electronic system that makes direct use of the Doppler effect is especially suitable for rocket development. The development of ballistic missiles and space vehicles requires a highly accurate, reliable, and all-weather instrumentation system. Most rockets are powered only during a relatively short portion of the flight; therefore, exceptionally high accuracy is required for that portion of the trajectory. To evaluate guidance and control systems and power plants while the vehicle is in the research and development phase, it is necessary to determine the trajectory to an even greater accuracy. The more common electronic tracking systems, such as radar, are not considered adequate.

Some optical systems, such as ballistic cameras with star calibration, produce the required position accuracy; but they are limited by their dependence on atmospheric conditions. Another serious objection, both to optical and radar tracking systems, is the fact that they are basically position measuring devices. Minor imperfections of the engines or the guidance and control systems are most often detected by comparing the observed velocity or acceleration with predicted values. Velocity can be determined from radar and optical data only by differentiating the position data; double differentiation is required in order to find acceleration. Slight noise in the position information is thus greatly magnified by this process, while Doppler systems yield velocity information without differentiation and require only one differentiation to obtain acceleration.

The demand for accurate and reliable trajectory data is further increased by the stringent flight safety requirements that must be fulfilled when ballistic missiles are fired. If it becomes necessary for one of the slower, air-breathing missiles to be destroyed for safety reasons, emergency measures can be taken to bring a winged vehicle to Earth near the point at which the malfunction occurred. Such is not the case when the offender is a ballistic missile far outside the atmosphere. If the vehicle is destroyed by radio command, the pieces will continue in a ballistic trajectory and may impact hundreds or even thousands of miles away. It is necessary to know when the potential impact point (the point at which the rocket would impact if thrust should terminate at a given instant) reaches the edge of the danger area, so that emergency action can be taken before life or property is endangered. Reliability is even more important in flight safety instrumentation than in systems used to properly evaluate vehicle performance. A failure in this equipment can result in the destruction of a perfectly good vehicle.

In the early stages of rocket development, it was sometimes necessary to make use of ground tracking stations as part of the guidance system. The velocity was measured by tracking stations in the launch area, and when it reached the value required to produce the desired range, the engine was cut off by radio command.

The original Doppler velocity cutoff system contained a ground transmitter and receiver, both located behind the launch site on a line tangent to the trajectory at the cutoff point. The on-board transponder received a signal from the ground transmitter, doubled the frequency, and retransmitted the resulting signal to the ground station. A signal from the same ground transmitter was doubled and compared with that returning from the missile. Before liftoff these two frequencies were exactly the same; but as velocity increased, the frequency received from the missile was shifted downward due to the Doppler effect, producing an audible beat between this signal and the second harmonic of the ground transmitter. When the beat reached a precalculated frequency, the cutoff command was initiated.

23.3 The Dovap System

A one-station system like that described above can measure only one component of velocity -- the component toward the station. In order to evaluate the performance of a missile, all components of both velocity and position are required. A Dovap (Doppler velocity and position) system was formed by adding additional stations to one of these velocity cutoff systems.

A typical Dovap system consists of a reference transmitter, three or more receiver stations, and a recording station. The transmitter, which operates on a frequency of about 37 Mc with an output power of 2 to 4 kw, radiates an unmodulated signal to the missile and to each of the receiver stations. A transponder in the missile receives the signal, amplifies it, doubles the frequency, and retransmits the second harmonic to the ground receiver stations. At each of these sites, the signal from the missile transponder and that from the ground reference transmitter are received and compared. The beat between the missile signal and the second harmonic of the reference is recorded at a central station.

Although the reference signal f_t is a constant 37 Mc, the signal received by the transponder is altered by the Doppler effect when the missile is in motion. If the missile is moving away from the transmitter the frequency received is $f_t - d$ where d is the Doppler shift. This frequency is doubled and retransmitted as $2f_t - 2d$. The return signal suffers an additional Doppler shift so that station R_1 receives a frequency of $2f_t - 2d - d_1$.

Station R_1 also receives the reference signal directing from the transmitter site. This reference is unaffected by the Doppler shift, as both the transmitter and receiver stations are stationary. The reference frequency is doubled at the receiver site and is beat with the missile signal to produce

$$2f_t - (2f_t - 2d - d_1) = 2d + d_1 \qquad (23.1)$$

This is an audio frequency that is proportional to the rate of change of the loop distance from transmitter to site R_1. The actual loop distance is found by integrating this frequency.

The receiver used to compare the signal from the missile with the frequency of the reference transmitter is a dual-channel, superheterodyne receiver with a common local oscillator shared by the two channels. The local oscillator frequency used by the 37 Mc channel is doubled and supplied to the mixer stage of the 75 Mc channel, producing an i.f. of 5 Mc for the data channel and 2.5 Mc for the reference channel. The 2.5 Mc i.f. is doubled and the two subtracted to form the Doppler beat.

The beat frequency from each station is recorded on 35-mm film together with coded timing pulses. As most of the stations are in remote locations, it is considered more convenient to relay the beat frequency to a central recording station, where accurate timing is available, than to relay the timing signals to the various sites and record each beat locally. This places all of the recording equipment in a central, easily accessible, location and reduces the remote receiver stations to relatively simple installations. It also has the advantage that one recorder can serve several sites.

The beat frequencies are transmitted to the recording station over telephone lines where the distances are short and where such lines are available. However, it is often found to be more economical to use an rf link. In the case of some of the more critical stations, rf links are used even when land lines are available, due to the increased reliability and improved frequency response. The rf link employs standard FM-FM telemetry equipment. A subcarrier oscillator, usually 52.5 or 70 kc, is frequency modulated with the audio beat and the resulting signal is then frequency modulated on an rf carrier in the 70 to 100 Mc range and transmitted to the recording site. There it is received and discriminated one time with a wide-band FM receiver to recover the modulated subcarrier, which is again discriminated to produce the original Dovap beat. Unlike the FM-FM system used for missile to ground telemetry, each carrier is usually modulated with only one subcarrier. The double modulation technique is necessary, however, in order to handle the extremely low beat frequencies encountered at liftoff.

At the recording station, beat signals varying in frequency from zero to about 2000 cycles are displayed on cathode-ray tubes and photographed with an oscillograph recording camera. The signal is placed on the horizontal axis with no sweep on the vertical axis. The time base is provided by the motion of the film, which is driven by a synchronous motor governed by a crystal controlled oscillator. Four cathode-ray tubes, presenting the beats from four stations, are mounted in front of each camera. Lamps, fed by coded timing pulses, are mounted between the cathode-ray tubes. The resulting films show four sine waves and several rows of dots and dashes produced by the timing lamps.

The beats are also recorded on magnetic tape, using FM recorders to extend the frequency range to zero. Originally these recorders were only used as back up for the cameras. In case of a camera failure, the tape record could be played back into the camera recording equipment to reconstruct the film. Equipment to read the magnetic tape directly was later developed, with the result that the cameras became secondary in importance to the tape recorders.

The film record is read by a stroboscopic film reader that counts the total number of cycles in each trace on the film and punches an IBM card, showing the subtotal and the time for every 0.5 sec of flight. The cycle counters used to reduce the magnetic tape produce a subtotal readout on digital tape for each 0.1 sec of flight. In both cases, the subtotal is read to 0.1 cycle.

The total number of cycles that have occurred up to a given time constitutes the integral of frequency and, therefore, indicates the total change in loop distance from liftoff to the given time. As the original loop distance at liftoff is known from a first order survey of the stations and of the launching pad, the actual loop distance from the transmitter to the missile to any receiver station can be determined at any time. The loop distance measurement from each receiver defines an ellipsoid with one of its foci at the receiver station and the other at the ground transmitter. Three such ellipsoids define a point in space. It is desirable, however, to use more than three receivers to allow a redundant calculation of x, y, z, $\dot{x}$, $\dot{y}$, and $\dot{z}$ for each point of the trajectory.

The Dovap system installed at Cape Canaveral to track the Redstone missile consists of eight receiver stations, all located within 20 miles of the launching pad at Cape Canaveral, and one transmitter station and one recording station, both located at the Cape. Another complete system of five receiver stations, a transmitter, and a recording station, on Grand Bahama Island and the nearby Cays, was used to cover the terminal portion of the trajectory. As each missile carried only one transponder, the two systems were not operated simultaneously. A switchover to the Dovap on Grand Bahama was made when the missile reached the point at which the geometry of that system became more favorable.

One limitation of the system is the ambiguity of its data. Dovap is basically a velocity measuring system; position data are obtained by integration. Therefore, to determine the constants of integration, one point of the trajectory must be known. This may be the liftoff point or some other point obtained from an independent system. The system on Grand Bahama, which cannot see the missile at liftoff, must rely on the Cape Canaveral Dovap or ballistic cameras for a tie-in. Furthermore, a momentary equipment failure could render subsequent data useless unless a tie-in can be obtained by extrapolating through the dropout. Fortunately, however, the system is so uncomplicated that equipment failures are extremely rare.

The accuracy of Dovap is difficult to express. The raw data give loop range measurements, and the accuracy of the position data calculated from these is a function of the position of the missile and the geometrical configuration of the stations. Experience indicates that loop distances can be measured to an accuracy of about 5:1,000,000. With the station layout used at Cape Canaveral, this can produce position errors to the order of 10 m when the missile is 100,000 m from the stations. Velocity accuracies of about 0.5 m/sec can be obtained up to that distance from the station complex, independent of the rocket velocity.

23.4 The Udop System

Dovap was a satisfactory tracking system for short range missiles (up to 200 miles range) and is still used extensively in the development of missiles of that type. When longer range missiles appeared, however, more accurate guidance was required and more accurate tracking was necessary to observe the performance of these new guidance systems. Dovap was obviously incapable of measuring velocity to the accuracy required for the Jupiter IRBM. An ultra-high-frequency Doppler (Udop) system was developed to meet these new accuracy requirements.

A major limitation of the Dovap system is its resolution, or the accuracy to which the best cycles can be counted. Each cycle represents a loop change of one wavelength or about 4 m. The beat can be counted to the nearest 0.1 cps, corresponding to 0.4 m of loop distance. If better resolution is required, it is desirable to use a shorter wavelength.

Dovap is again limited in that a single transmitter is used to supply a reference signal to the missile and also to the ground stations. It is desirable that the antenna that radiates the signal to the missile be located very near the ground to prevent multipath reception in the missile. If the antenna is located on a tower, two signals will reach the transponder — one directly from the antenna on the tower and another reflected from the ground or sea. The relative length of these two paths varies as the elevation of the missile changes. The reference signals to the receiver stations are not disturbed by this type of multipath because the elevations of the ground stations are fixed. Therefore it would be desirable to use a different antenna to supply reference to the receiver stations. This antenna could be located on a pole or tower, providing line-of-sight transmission to receiver sites beyond the horizon from the transmitter. Use of two antennas is impractical, however, when both reference signals are of the same frequency.

It is impossible to build an antenna that would radiate a signal to all the receiver stations without also radiating some energy to the missile, where it would interfere with the signal from the other antenna on the ground. A more practical approach uses two harmonically related reference signals, both derived from the same crystal oscillator but radiated at different frequencies. For example, an 18.5 Mc transmitter with an antenna on a pole might supply reference to the Dovap ground stations, while a 37 Mc transmitter, using the same exciter, interrogates the missile from an antenna on the ground. The transponder doubles the 37 Mc (less any Doppler shift), and the receivers multiply the 18.5 Mc reference by four to produce 74 Mc. Unfortunately, 18.5 Mc and all other frequencies below 30 Mc are too noisy for this type of service. The plan works much better if the whole system operates at much higher frequencies.

Another objection to Dovap frequencies is encountered when missiles begin to travel higher into the ionosphere. Vhf frequencies suffer severe phase shifts when they pass through the ionosphere. It is known that uhf frequencies, on the other hand, are only slightly affected. Flame effects are also less severe at higher frequencies.

In addition to the phase shifts caused by ionosphere and flame, these two effects combine to produce rapid variations in attenuation, both in the transmitter-to-missile path and in the missile-to-receiver path. If actual dropouts occur, they are usually of sufficiently short duration to permit extrapolation of data through them; but fluctuations in signal level are difficult to handle by the present Dovap receiver. Changes in signal strength, even when they do not constitute a complete dropout, cause phase shifts in the receiver. It is possible, at the present state of the art, to develop a receiver with phase shift substantially independent of signal strength. However, because of other limitations of the system, it is considered impractical to invest in a research and development project to produce a new Doppler receiver at these frequencies.

The most urgent need was for a more accurate measurement of cutoff velocity for the Jupiter missile. A single station was installed to produce these velocity data and, at the same time, to investigate the feasibility of a uhf Doppler position measuring system. A uhf transmitter, transponder, and ground receiver, developed as part of the Corporal missile system, was available. The first station was an interrogator transmitter with a frequency of about 450-Mc. This signal was doubled by the missile transponder and reradiated to a ground receiver that was located near the transmitter. A sample of the 450-Mc reference was doubled and sent to the receiver over a cable. Only one receiver station could be used because the receiver did not have a reference channel and required a high level reference signal. Results were very encouraging. The system produced the resolution necessary for the velocity and proved that the combined effects of flame and ionosphere were greatly reduced.

The first Udop system could only measure one loop range, however, and as mentioned above, three or more loop measurements are required for position and velocity calculations. It was necessary to combine this loop measurement with others from the Dovap stations in order to determine the three components of velocity. The site for the one station was selected so that it would be almost directly behind the missile at cutoff and would become the strongest station in the system during that critical portion of the flight.

Before more stations could be added, a receiver with a reference channel had to be built. A contract was let for the development of a dual-channel uhf receiver which would not produce objectional phase shifts for changes in signal strength. The reference channel made it possible for widely separated Udop receiver stations to be supplied with a common reference frequency, coherent with the signal used to interrogate the transponder.

Unlike the Dovap system, Udop does not attempt to make a single reference transmitter perform the dual function of interrogating the on-board transponder and supplying reference to ground receiver stations in all directions, but uses a dual-reference transmitter that produces a 50-Mc and a 450-Mc reference system from the same 25-Mc source. One antenna, located on the ground, radiates 1000 w at 450 Mc to interrogate the missile transponder, which doubles the frequency and reradiates 900 Mc, plus or minus Doppler shift, to all ground receiver stations. Another antenna, located on an 80-ft pole at the transmitter station, radiates 1000 w at 50 Mc to all receiver stations. Each receiver picks up the 50-Mc reference, multiplies it by 18, and compares the resulting 900 Mc with the 900 Mc, plus or minus Doppler, from the transponder. The difference between these two frequencies is the Udop beat, a tone which varies from zero at liftoff to about 30 kc at the cutoff velocity of a missile.

The beat frequency is transmitted to a central station where the beats from all stations are recorded on magnetic tape. For this data link, a data transmitter with a frequency response substantially flat from 1 cps to 60 kc was developed. To cover the first few seconds, before the beat rises to 1 cps, the outputs of the receivers near the launch site are transmitted to the recording station over land lines during the early part of the flight. The more distant stations do not encounter this problem, as they did in the Dovap system, because the Udop beat is already above 1 cps when the missile appears on the station horizon.

The configuration of the Cape Canaveral Udop system is the same as that used for Dovap, and the two systems share the same stations. One receiver is always located within a few hundred meters of the launch pad. In some cases, when very accurate data are required for the liftoff phase, a ground station antenna is also placed on the pad near the base of the missile. Three more stations are located within 5 km of the launch pad and three others at distances of 20 to 30 km. Although only three receivers are required to determine position and velocity, the optimum configuration of a three station system varies with the position of the missile. The close-in stations are of more value in the early part of the flight; the extended base line stations become more significant as the distance of the missile increases. Furthermore, a redundant solution, using all stations, yields higher accuracy than can be obtained from the optimum combination of three. Also an indication of the accuracy of the final results can be obtained from internal agreement of the redundant data. An error in counting the cycles from one station can be spotted immediately by this method. A redundant system has the additional advantage that the loss of any one station can be tolerated with only slight loss of accuracy. The Udop system is designed so that failure of any one component in the ground system cannot cause a complete loss of data.

In addition to the Udop stations mentioned above, there is another Udop system in the Bahama Islands 200 miles downrange from Cape Canaveral. This system consists of a transmitter station, a recording station, and five receiver stations, located on Grand Bahama Island and the smaller islands of the Little Bahama Bank. This system was installed primarily for missiles that impact in that area, but also supplements the uprange system on some other flights.

The two Udop systems do not interrogate the transponder at the same time. A switchover is performed during flight. At a preselected time, a voice command is given to switch off the uprange interrogator and turn on the 450-Mc transmitter of the Grand Bahama system. The uprange and downrange stations cannot function as a single giant Udop system because neither of the 50-Mc transmitters can supply a reference signal to stations in the other system. Both 50-Mc transmitters remain on throughout the flight (they are not switched as are the 450-Mc interrogators), but they do not have exactly the same frequency and phase, so the two systems are not coherent. After switchover, the downrange stations become an elliptical system (i.e., each station measures loop distance and defines an ellipsoid in space); and the uprange configuration, which no longer controls the transponder, becomes a hyperbolic system. The loop range measurement from each uprange station now contains an error, namely the phase and frequency difference between the uprange and downrange reference transmitters — but the error is the same for each receiver station. By subtracting the cycle counts from two such stations, a loop difference can be determined. Three loop differences (four receiver stations) can determine a point in space.

A hyperbolic system is less accurate than an elliptical system, except for velocity components in certain directions preferred by the system geometry; but when data from the two systems (uprange and downrange) are combined, there is a resulting increase in overall accuracy. It should be noted, though, that another tie-in point is required after the interrogator switchover.

The error between the two reference transmitters is greatly reduced by use of atomic clocks to provide the excitation for the transmitters. The accuracy obtainable from atomic frequency standards, at present, is not sufficient to enable the two systems to be considered coherent, however.

Another method of combining widely separated stations into one system was tried using Dovap stations. Some of the downrange sites near the submarine cable were supplied with a reference tone from the cable and the uprange interrogator signal was derived from the same tone. The resulting increase in accuracy was somewhat less than expected, presumably due to phase shifts in the cable.

Improvements in the Udop system are directed toward increased sensitivity of the receiving equipment. A phase-locked receiver has been developed for Udop, making possible the use of smaller on-board packages and greatly extending the distances over which the system can operate. Phase-locked receivers are now installed at four of the uprange stations and are being installed at some of the downrange stations.

23.5 The Beat-Beat System

The Dovap and Udop tracking systems are not real time systems. Emphasis is placed on accuracy rather than speed of reduction. The raw data are recorded on tape and several days may be required for the data reduction process before velocity and position information are available. This delay is not too objectionable when the data are to be used for evaluation of vehicle performance, but there is a need for some trajectory information in real time so the Flight Safety Officer may know immediately whether the path being followed is one that could result in an impact in populated areas. It is necessary that the time required for processing these data be limited to a fraction of a second. The Beat-Beat system is a simplified Doppler tracking facility designed to provide this type of information.

The original Beat-Beat system consisted of a pair of Dovap receiver stations placed symmetrically about the flight line and modified to give the angle off course in real time. A later model of the system uses tunable receivers and can track telemetry transmitters or almost any rf source between 55 and 960 Mc. As long as the vehicle remains in a plane equidistant from the two stations, the Doppler beat frequency at each station is exactly the same. When the vehicle deviates to the left or right, one beat frequency will increase and the other will decrease.

The difference between these two beats, or the Beat-Beat, is a function of lateral velocity. The total number of cycles of the difference

$$F = \int_0^t (f_1 - f_2)\, dt \tag{23.2}$$

is directly proportional to the difference between the distances from the vehicle to the two stations. If the distance is great enough to allow the lines from the vehicle to the Beat-Beat sites to be considered parallel, it can be seen from Fig. 23.1 that $\sin \epsilon = \frac{\lambda F}{B}$, where B is the distance between stations, ϵ is the angle between the direction to the missile and the reference plane, and λ is the wavelength. The base line B is normally 200 λ. Therefore $\sin \epsilon = \frac{F}{200}$.

The beat output from a normal Dovap receiver will vary from zero to several hundred cycles per second during a missile flight. In Beat-Beat it is necessary to subtract the two beat frequencies in real time, using the simplest and most reliable method available. To simplify this task, a bias frequency is added to the two Dovap beats. This is accomplished by supplying 37.001 Mc from a crystal-controlled generator to the two Beat-Beat receivers over coax cable to replace the 37 Mc reference signal normally received from the Dovap transmitter. The receiver outputs will then remain at least 2 kc when the vehicle is on the pad and will increase in frequency as the velocity increases. The difference between the two beats, however, is unaffected by the bias.

The two beats are fed into a ring modulator that produces the Beat-Beat. A second ring modulator is fed by the same two signals after one of them has been shifted 90 deg. The result is a second Beat-Beat, 90 deg out of phase with the first. The two ring modulators drive a two-phase synchronous motor geared to a data potentiometer. Strip chart recorders, fed by this potentiometer, are used to display the angle off course in the blockhouse and at the safety officer's console in central control.

The original installation used standard Dovap receivers and was only capable of tracking the Dovap transponder; but Beat-Beat is a hyperbolic system and does not make use of the fact that the transponder is coherent. It can track a free-running beacon. The error in the beacon frequency is cancelled when the two beats are subtracted to produce the Beat-Beat frequency. A more versatile Beat-Beat system was required — one which could track a telemetry package on missiles not carrying a Dovap transponder. Most missiles carry several telemetry transmitters, so it would be desirable to change frequencies quickly in the event of a failure of an

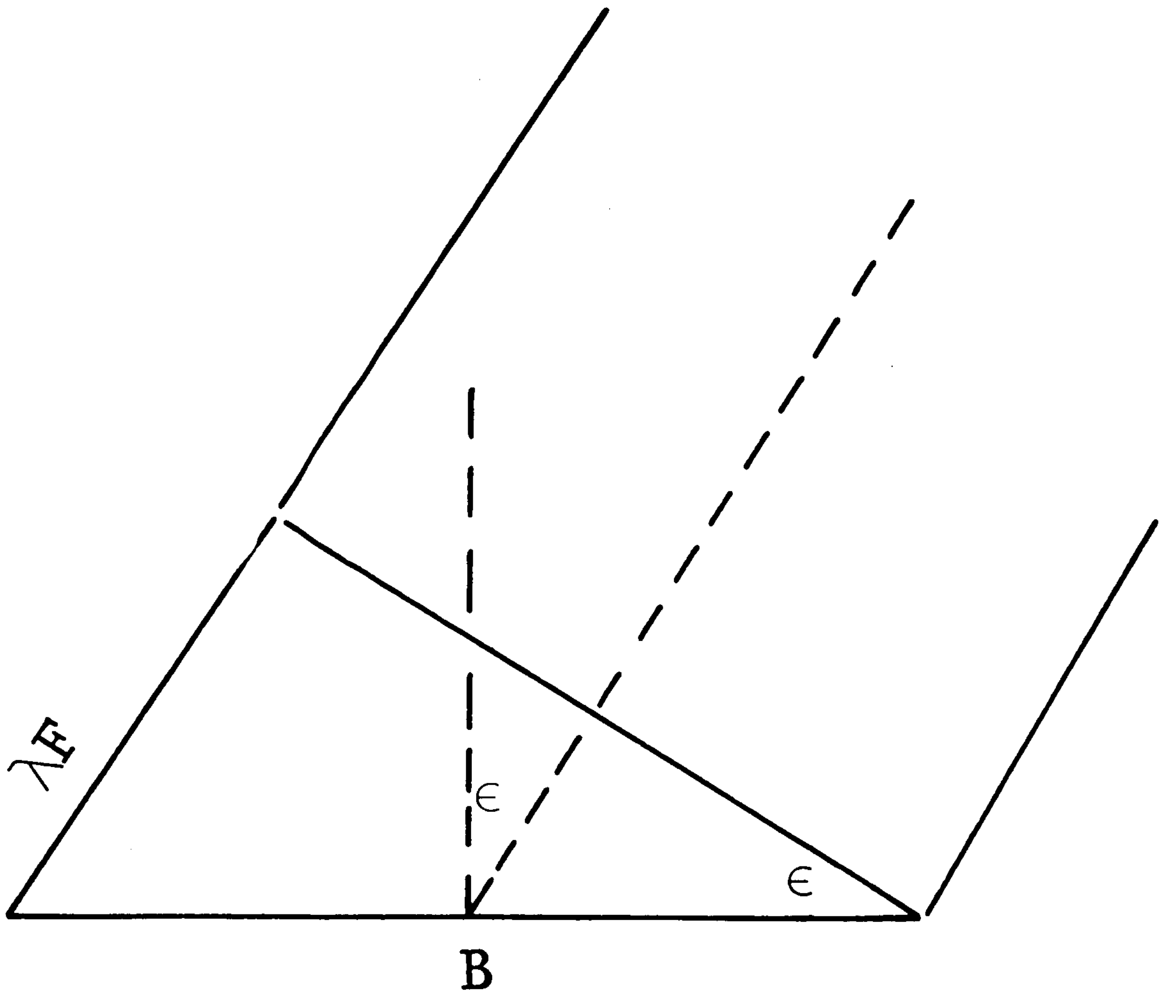

Fig. 23.1 Diagram illustrating $\sin \epsilon = \frac{\lambda F}{B}$.

on-board package, or to operate a backup system that would track a different rf source. After the Dovap Beat-Beat had proved its worth as a flight safety system, Beat-Beat Mark II was developed.

A manufacturer of telemetry receivers was asked to repackage two of his standard models on a single chassis, sharing a common local oscillator so that the two channels would be coherent. A mechanical servo has been developed that compares the two i.f. signals from the new receiver and causes a motor to rotate at the difference frequency. The modulation is removed and the two i.f. frequencies are converted to 400 cps by a synchronous detection process. A control transformer shifts the phase of one of the 400 cycle i.f. signals to keep it in phase with the i.f. from the other channel of the receiver. The resulting phase error (if any) is detected and used to drive the servo motor that positions the control transformer. A data potentiometer, geared to the same servo motor, feeds the recorders at the safety officer's console as it did in the earlier system.

To determine whether a vehicle will impact outside the target area, the safety officer must know the angle off course and the rate of change of the angle. To assist him in determining this, the predicted curve and a family of curves, indicating the maximum slope which the recorder trace can be allowed to assume for each value of ϵ for each second of flight, are calculated and drawn on the chart before the firing.

Another cause for concern to the safety officer is the possibility that a vertical takeoff vehicle will continue in vertical flight or program in the opposite direction. To guard against this type of malfunction, another Beat-Beat baseline was installed symmetrically about a plane passing through the launching pad, perpendicular to the flight line. This system detects any slight deviation forward or backward from the vertical. A predrawn curve indicates the path which the missile is expected to follow, and a family of curves, similar to that mentioned above, indicates the slope which the recorder trace can assume without endangering the area behind the pad.

Beat-Beat is less accurate than Dovap because of the shorter base line. Because reliability, rather than high accuracy, is the primary concern in flight safety instrumentation, the system was designed for an accuracy of 1 mil. Comparison of Beat-Beat data with trajectory information from more accurate systems, operating during actual flights, indicates that the accuracy achieved is well within this limit.

23.6 The Radop Concept

It was stated earlier that Doppler systems have the unique capability of measuring rocket velocity directly, thereby having definite advantages over other instrumentation types. However, the Doppler systems actually measure loop velocities only and are not able to produce velocity resolution into specified coordinate directions, unless provided with some information extraneous to the system. In the classical solution, this extraneous information is the tie-in point mentioned above. Two conditions must be met to make the introduction of the tie-in point effective throughout the entire period of Doppler tracking coverage. No signal dropout must occur, or the entire remaining portion of a station recording becomes worthless. Extremely high position accuracy, usually obtainable only by optical triangulation, is required for the tie-in point. Geometry deterioration increases as the rocket travels away from the station complex.

For a Jupiter missile trajectory, the position error of a tie-in point provided at about 40 sec flight time causes a tenfold position error at the time of missile cutoff. On the other hand, the inherent simplicity and reliability of Doppler instrumentation has raised the desire to employ such systems in places other than heavily instrumented missile launch areas to support vehicle programs requiring world-wide tracking. In such applications, it is usually impossible to obtain a tie-in point of the required accuracy, and an uninterrupted signal cannot be postulated. Two ways are open to overcome the difficulties. By employing at least six Doppler receiver stations simultaneously, rocket position and velocity can be determined analytically from the six observed loop velocities. Analysis shows, however, that at least a dozen receiver stations are required to achieve acceptable data accuracy. The reason for this is that position accuracy is determined largely by the ability of the system to resolve observed loop velocities into specified coordinate directions. Because the number of stations required to do this with greater accuracy is prohibitive in terms of real estate, logistics and operating effort, position determination by this method is rather weak.

At this point, the Radop (Radar, Doppler) concept is introduced to show a feasible solution. Radop is called a concept, rather than a system, because the necessary tracking equipment has been available all the time. The only new aspect is a novel method of raw data reduction using results of existing instrumentation systems.

As pointed out above, any Doppler system requires some extraneous vehicle position information. In the Radop concept, radar position data are used for this purpose. Admittedly, position accuracy so obtained will be inferior if compared with the classical Doppler data reduction method employing a tie-in point. It can be shown that, for suitable station configurations, the limited position accuracy has negligible effect on the process of resolving Doppler loop velocities into specified coordinate directions. Furthermore, tracking data requirements emphasize velocity accuracy rather than position accuracy. The mathematical solution employs azimuth, elevation angle, and slant range from at least one radar, as well as loop velocities from at least three Doppler receiver stations. Any additional radar on Doppler station available allows a least-squares solution for vehicle position and velocity. Tentative computations using Cape Canaveral Udop and C-band radar data have affirmed the feasibility of the Radop concept by comparison with results of standard data reduction methods employed by the Atlantic Missile Range.

In addition to being more suitable for instrumenting remote tracking complexes abroad, the Radop concept has a great potential as a flight safety tracking scheme with virtually instantaneous output. Already, C-band radar data are being accepted in real time by a high-speed computer at the Atlantic Missile Range to compute the instantaneous impact point. Necessary smoothing of radar position data, however, causes a delay of several seconds between reception of data and impact point output. Any such delay poses a substantial limitation on the allowable flight azimuth, a restriction being felt more and more as lunar and planetary missions increase in number and significance. Provided that the output of three or more Udop receivers could be digitized and fed into the same computer along with the radar data, unsmoothed radar and Doppler data would provide sufficiently accurate position and velocity data to calculate the instantaneous impact point. The only delay so encountered would be a fraction of a second spent for the computation process.

23.7 Orbital and Deep Space Applications

Doppler tracking systems have been used for the development of ballistic missiles for almost two decades. Weight and size of on-board equipment such as transponders, antennas, and power supplies were almost unlimited due to the payload capability of such a vehicle. Furthermore, distances to be covered were very short compared with requirements of orbital, lunar, and interplanetary missions.

A radical change from the old concept was required with the firing of the first satellites, with very limited payload capabilities. For best weight utilization, a one-way Doppler system was used with a solid-state transmitter providing about 10 mw of radiated power. To achieve a vary narrow noise bandwidth, a highly sensitive receiver, using phase lock technique, was necessary. In addition, two interferometer systems, arranged 90 deg from each other, provided angle measurements. Such data, obtained from ground stations with a favorable station geometry, furnished position and velocity as well as orbital parameters.

As missions become more sophisticated, corresponding improvements are required for both the on-board and the ground instrumentation. To eliminate any drift in frequency of the on-board oscillator, a two-way Doppler tracking system must be employed. The use of a transponder will guarantee highly accurate Doppler data because of the coherent receiving capability. To keep size and weight within an acceptable limit, a solid-state transponder is preferred. In general, such a transponder consists of a complete receiver and a low-level transmitter. Deep space missions require additional amplifiers to increase the radiated power to the necessary level. Precise determination of spatial coordinates and orbital elements at interplanetary distances requires two-way Doppler data from a number of stations; and, whenever possible, station geometry should be such that continuous coverage is provided. However, the final arrangement of stations depends on such parameters as trajectory, accuracy requirements, and minimum trackable elevation angle.

A marked improvement is obtained by providing additional range data. This is accomplished by independent systems as described above in Radop or by measuring the Doppler shift of a modulation frequency on the cw carrier. For such a range measurement, the signal has to originate in the ground station that makes the two-way operation mandatory. The ultimate tracking system should be able to provide two angles, range, and range rate simultaneously.

Spacecraft transmitters of early satellites were also used for transmission of narrow-band telemetry information. Future missions will require an information bandwidth much wider than that needed for tracking purposes. This will make the use of a separate tracking transponder highly desirable.

Lunar and interplanetary distances can be covered, from the ground to the spacecraft, by narrow beam antennas with a transmitting power of 10 kw or more. Transmitting power as high as 100 kw is considered for future missions.

To guarantee the most reliable operation on a space mission, an extensive effort is necessary in the design of on-board antenna systems. Experience with early satellites shows that most missions require two different tracking antennas for satisfactory results. The near-Earth portion of the flight is best covered by an isotropic or omnidirectional antenna. Such a system consists of a number of antennas with overlapping patterns. The result is a radiation pattern reasonably isotropic. For lunar and interplanetary distances, a high-gain antenna on board the spacecraft is an absolute necessity. For most known missions, the high-gain antenna will be an erectable or inflatable parabolic antenna. Steerable parabolics are considered for some missions.

Because of serious limitations of weight, space, and power in a spacecraft, the radiated power of an on-board transponder is very limited. To compensate for these shortcomings and to guarantee reliable operation under the most severe conditions, a special effort is demanded at the receiver site. Two-turn helical antennas, used for tracking early satellites, have been replaced by parabolic reflectors with high gain and narrow beamwidth for reduction of possible interference. Jet Propulsion Laboratory's Deep Space Instrumentation Facility uses steerable 85-ft, parabolic-reflector antennas that can be controlled manually or by error signals from the tracking receiver. New large aperture antenna systems are being planned. An advanced antenna system with a trackable dish approximately 250 ft in diameter would provide improvement of approximately 10 db over existing systems.

Very sensitive receivers applying phase lock technique were used for tracking the first satellites. For tracking lunar and interplanetary probes, the threshold of the ground receiver system must be further reduced if reliable data are to be expected. This assurance can be accomplished by the use of low-noise preamplifiers. Traveling wave tube amplifiers, parametric amplifiers, and maser amplifiers are used in tracking experiments with promising results. Jet Propulsion Laboratories was successful in receiving Venus-reflected Doppler and range signals using a maser amplifier followed by a parametric amplifier as a preamplifier. The receiver is phase coherent with a very narrow bandwidth. This experience shows that passive tracking of a probe with an ultra high sensitivity setup is possible. Satellites without transponders, or with transponders that fail to radiate, can be tracked passively and the reflected signal can provide velocity and range data.

Lunar and interplanetary missions will require manned or unmanned orbital operation for rendezvous or in-orbit assembly that will require an on-board range and range rate measuring system. Such a homing system will be necessary to operate as an acquisition system and for the final approach. Systems so developed might well prove to be an important part of the instrumentation for an actual landing maneuver.

Tracking of the first satellites was accomplished on a frequency of 108 Mc. This frequency was only used with a one-way system. When more accurate Doppler data became necessary, a coherent system with a frequency of 890 Mc to 960 Mc was employed. But even these frequencies will be replaced by an S-Band frequency in the future. The higher frequencies will allow the use of smaller antennas with better protection from interference due to a narrower beamwidth. Even higher frequencies in the X-Band are considered for Doppler measurements on orbital rendezvous and deep space missions.

Whatever the scientific requirements of a future space mission may be, Doppler data will always be of utmost importance. The state of the art will have to improve continually to meet more stringent requirements as future missions become more and more complex.