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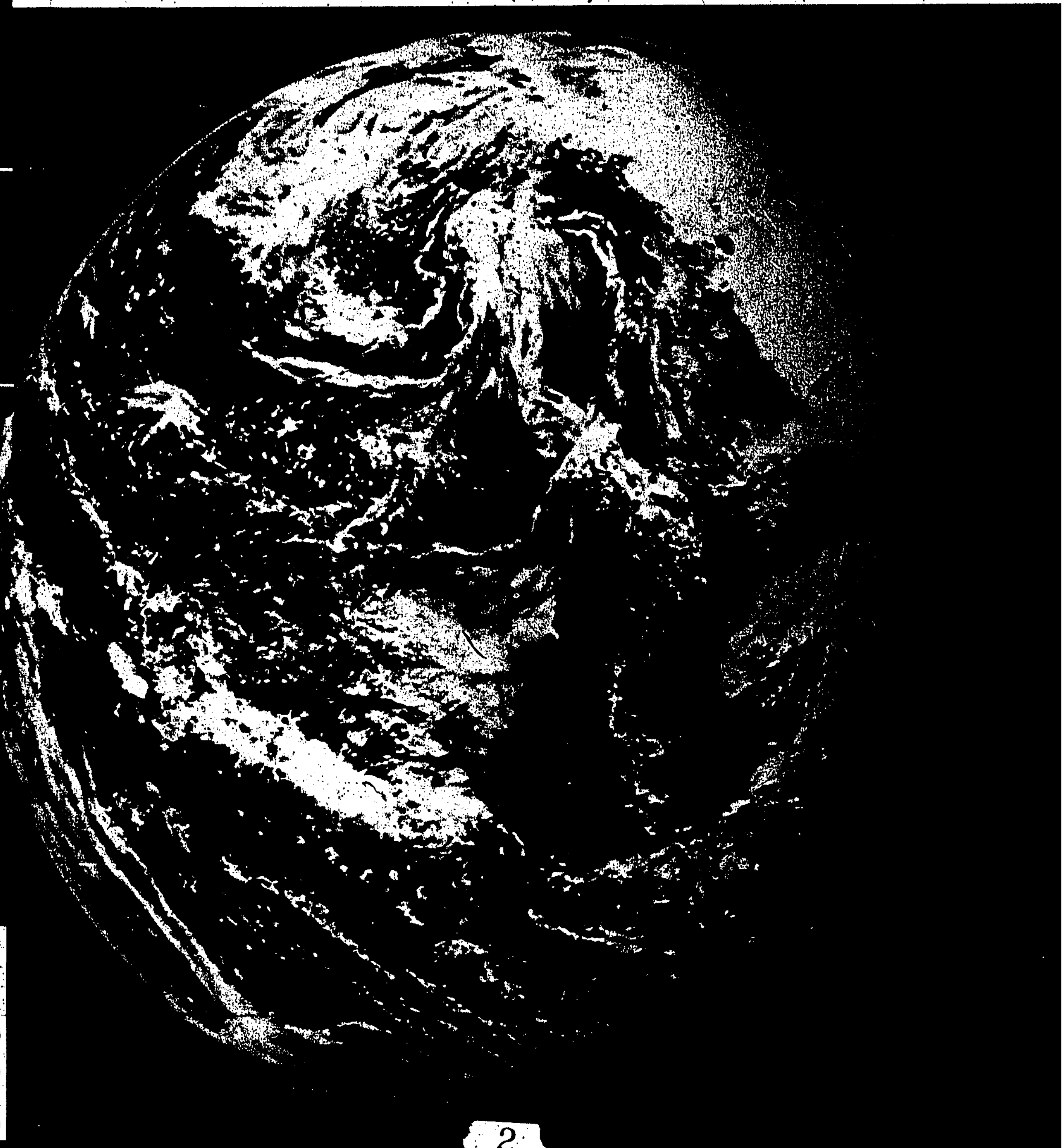
ABSTRACT

This booklet is the fourth in a series of nine that describe the Apollo-Soyuz mission and experiments. This set is designed as a curriculum supplement for teachers, supervisors, curriculum specialists, textbook writers, and the general public. These booklets provide sources of ideas, examples of the scientific method, references to standard textbooks, and descriptions of space experiments. There are numerous diagrams, as well as questions for discussion (with answers) and a glossary of terms. The series has been reviewed by selected high school and college teachers nationwide. This booklet discusses the Doppler Effect, the earth's gravity anomalies, the "low-low" satellite technique, and the "high-low" satellite technique. (MA)

Apollo-Soyuz Pamphlet No. 4:

Gravitational Field



Apollo-Soyuz Experiments In Space

This is one of a series of nine curriculum-related pamphlets for Teachers and Students of Space Science

Titles in this series of pamphlets include:

EP 133 Apollo-Soyuz Pamphlet No. 1: The Flight
EP 134 Apollo-Soyuz Pamphlet No. 2: X-Rays, Gamma-Rays
EP 135 Apollo-Soyuz Pamphlet No. 3: Sun, Stars, In Between
EP 136 Apollo-Soyuz Pamphlet No. 4: Gravitational Fields
EP 137 Apollo-Soyuz Pamphlet No. 5: The Earth from Orbit
EP 138 Apollo-Soyuz Pamphlet No. 6: Cosmic Ray Dosage
EP 139 Apollo-Soyuz Pamphlet No. 7: Biology in Zero-G
EP 140 Apollo-Soyuz Pamphlet No. 8: Zero-G Technology
EP 141 Apollo-Soyuz Pamphlet No. 9: General Science

On The Cover

An [illegible] View of the Earth

Apollo-Soyuz Pamphlet No. 4:

Gravitational Field

Prepared by Lou Williams Page and Thornton Page From Investigators' Reports of Experimental Results and With the Help of Advising Teachers

National Aeronautics and Space Administration

Washington, D.C. 20546
October 1977

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Preface

The Apollo-Soyuz Test Project (ASTP), which flew in July 1975, aroused considerable public interest; first, because the space rivals of the late 1950's and 1960's were working together in a joint endeavor, and second, because their mutual efforts included developing a space rescue system. The ASTP also included significant scientific experiments, the results of which can be used in teaching biology, physics, and mathematics in schools and colleges.

This series of pamphlets discussing the Apollo-Soyuz mission and experiments is a set of curriculum supplements designed for teachers, supervisors, curriculum specialists, and textbook writers as well as for the general public. Neither textbooks nor courses of study, these pamphlets are intended to provide a rich source of ideas, examples of the scientific method, pertinent references to standard textbooks, and clear descriptions of space experiments. In a sense, they may be regarded as a pioneering form of teaching aid. Seldom has there been such a forthright effort to provide, directly to teachers, curriculum-relevant reports of current scientific research. High school teachers who reviewed the texts suggested that advanced students who are interested might be assigned to study one pamphlet and report on it to the rest of the class. After class discussion, students might be assigned (without access to the pamphlet) one or more of the "Questions for Discussion" for formal or informal answers, thus stressing the application of what was previously covered in the pamphlets.

The authors of these pamphlets are Dr. Lou Williams Page, a geologist, and Dr. Thornton Page, an astronomer. Both have taught science at several universities and have published 14 books on science for schools, colleges, and the general reader, including a recent one on space science.

Technical assistance to the Pages was provided by the Apollo-Soyuz Program Scientist, Dr. R. Thomas Giuli, and by Richard R. Baldwin, W. Wilson Lauderdale, and Susan N. Montgomery, members of the group at the NASA Lyndon B. Johnson Space Center in Houston which organized the scientists' participation in the ASTP and published their reports of experimental results.

Selected teachers from high schools and universities throughout the United States reviewed the pamphlets in draft form. They suggested changes in wording, the addition of a glossary of terms unfamiliar to students, and improvements in diagrams. A list of the teachers and of the scientific investigators who reviewed the texts for accuracy follows this Preface.

This set of Apollo-Soyuz pamphlets was initiated and coordinated by Dr. Frederick B. Tuttle, Director of Educational Programs, and was supported by the NASA Apollo-Soyuz Program Office, by Leland J. Casey, Aerospace Engineer for ASTP, and by William D. Nixon, Educational Programs Officer, all of NASA Headquarters in Washington, D.C.

Appreciation is expressed to the scientific investigators and teachers who reviewed the draft copies; to the NASA specialists who provided diagrams and photographs; and to J. K. Holcomb, Headquarters Director of ASTP operations, and Chester M. Lee, ASTP Program Director at Headquarters, whose interest in this educational endeavor made this publication possible.

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1 Introduction

After 4 years of preparation by the U.S. National Aeronautics and Space Administration (NASA) and the U.S.S.R. Academy of Sciences, the Apollo and Soyuz spacecraft were launched on July 15, 1975. Two days later at 16:09 Greenwich mean time on July 17, after Apollo maneuvered into the same orbit as Soyuz, the two spacecraft were docked. The astronauts and cosmonauts then met for the first international handshake in space, and each crew entertained the other crew (one at a time) at a meal of typical American or Russian food. These activities and the physics of reaction motors, orbits around the Earth, and weightlessness (zero-g) are described more fully in Pamphlet I, "The Spacecraft, Their Orbits, and Docking" (EP-133).

Thirty-four experiments were performed while Apollo and Soyuz were in orbit: 23 by astronauts, 6 by cosmonauts, and 5 jointly. These experiments in space were selected from 161 proposals from scientists in nine different countries. They are listed by number in Pamphlet I, and groups of two or more are described in detail in Pamphlets II through IX (EP-134 through EP-141, respectively). Each experiment was directed by a Principal Investigator, assisted by several Co-Investigators, and the detailed scientific results have been published by NASA in two reports: the ASTP Preliminary Science Report (NASA TM X-58173) and the ASTP Summary Science Report (NASA SP-412). The simplified accounts given in these pamphlets have been reviewed by the Principal Investigators or one of the Co-Investigators.

As described in Pamphlet I, the orbit of a spacecraft is controlled by the Earth's gravitational field. If the Earth's gravity is "smooth," the spacecraft moves in an elliptical orbit at a predictable velocity. However, if there are irregularities in the Earth's gravity, a spacecraft in low orbit will speed up and slow down as it passes over them. Such irregular motion has been observed for spacecraft in orbit around the Moon and has been looked for on NASA missions passing other planets.

For many years, the acceleration of gravity g was thought to be the same on all parts of the Earth's surface. Then it was discovered that g is higher than normal in some regions and lower than normal in others. These regions are called "gravity anomalies," and they are caused by the high or low density of the Earth's crust. Detecting them is useful in locating ore deposits, coal, oil, and gas. Two of the Apollo-Soyuz experiments were designed to detect gravity anomalies from the motions of spacecraft.

Experiment MA-089, Doppler Tracking, was supervised by G. C. Weiffenbach of the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. The objective was to detect gravity anomalies by measuring the changes in the distance between two satellites (the Apollo Command Module and the Docking Module) as they passed over an anomaly and were accelerated by its higher gravitational force. Both satellites were in the same low orbit, and this technique became known as the "low-low" method.

The Principal Investigator for Experiment MA-128, Geodynamics, was F. O. Vonbun of the NASA Robert H. Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The experiment was designed to detect gravity anomalies by measuring the changes in distance between the Apollo spacecraft and the ATS-6 satellite, which was in a much higher orbit. This procedure became known as the "high-low" method, in contrast to the "low-low" method of Experiment MA-089.

2 The Doppler Effect

When an automobile blowing its horn or a train blowing its whistle passes you, there is an obvious change in the pitch of the sound that you hear. The pitch becomes higher as the vehicle approaches and lower as it recedes. In 1842, Christian Doppler, an Austrian scientist, pointed out that this change is to be expected when any source of periodic output such as sound waves moves toward or away from an observer. The pitch (the higher or lower tone) of sound is a measure of the frequency of sound waves, which are periodic changes in air pressure that we can hear. The Doppler effect is usually illustrated by a diagram that shows sound waves crowded together in the direction of the motion of the train whistle and spread out on the other side. Figure 2.1 gives a more precise explanation.

The train whistle gives out sound waves of frequency f, about 500 hertz (500 cycles/sec). These waves travel through the air at the velocity of sound v_S, about 320 m/sec. As the train approaches at velocity v, its distance from a listener (observer) standing near the track is decreasing. Therefore, each sound wave has less distance to travel than the preceding wave (Fig. 2.1). The "period" T of the sound wave is $T = 1/f$, which is the time interval between waves, or about 0.002 second for the train whistle. In the interval T, the train moves a distance vT. The next sound wave thus arrives early by vT/v_S seconds, and the period of sound waves heard by the observer is $T' = T - (vT/v_S)$. The frequency that he hears is $f' = f + (vf/v_S)$, and the wavelength λ he measures is $\lambda' = \lambda - (v\lambda/v_S)$.

The *Doppler shift* is

$$\Delta T = T' - T = -vT/v_S$$

or

$$\Delta f = f' - f = +vf/v_S$$

or

$$\Delta\lambda = \lambda' - \lambda = -v\lambda/v_S$$

where T, f, and λ are the period, frequency, and wavelength, respectively, of the train-whistle sound as heard or measured on the train. As Doppler explained the phenomenon more than a century ago, the same reasoning applies to light waves or radio waves, except that they move with a much larger speed, 3×10^8 m/sec (the velocity of light c). Light waves from the moving train would thus be shifted to a higher frequency ("blue-shifted" by $\Delta f = +fv/c$ or $\Delta\lambda = -\lambda v/c$) as the train approaches. The light waves would be "red-shifted" (negative Δf, positive $\Delta\lambda$) as the train recedes. The terms "blue-shifted" and "red-shifted" are used because higher frequency waves of visible light are blue and lower frequency waves are red, as described in Pamphlet II. The shift is very small for normal train velocities (60 km/hr or 16.7 m/sec or 37 mph), which are less than one-millionth of the velocity of light. However, most satellites, planets, stars, and other astronomical objects move much faster than trains (from 7 km/sec to hundreds of kilometers per

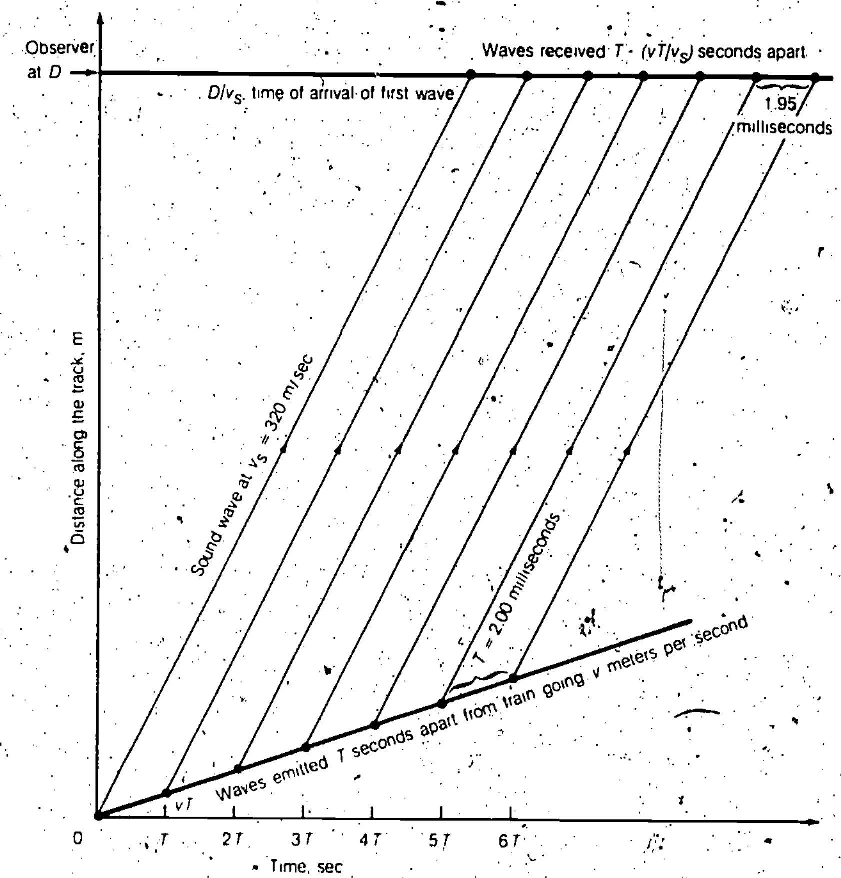

Figure 2.1 **Distance-time plot showing the Doppler shift for sound waves from an approaching train with *T* of 2 milliseconds. Waves received by the observer have *T'* of 1.95 milliseconds.**

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second). The small Doppler shifts of radio waves from a radar on a police car are used by police to show when drivers are exceeding the speed limit. (The Doppler shift is doubled when the radio waves are reflected from a moving car.)

A The Discovery of Mascons on the Moon

Radio techniques can measure frequency very accurately. They were used to discover the "mascons," which are concentrations of mass just under the Moon's surface, from the very small accelerations of Moon orbiters that were broadcasting radio waves to receivers on Earth. The Doppler effect results from the movement of the sender or the receiver toward or away from each other. Therefore, it is the *component* of v along the line from the moving orbiter to the receiver on Earth that must be used in the Doppler formula $\Delta f = fv/c$. This is shown in Figure 2.2. Radio engineers at the NASA Jet Propulsion Laboratory (JPL) tracked NASA's five Lunar Orbiters and measured Δf with high precision. They turned the Doppler formula around and computed $v = c\Delta f/f$ with an accuracy of a few millimeters per second. Taking into account the Earth's motion and the direction of motion of the Lunar Orbiter satellite, the engineers calculated the orbital speed of the satellite, second by second. They knew that the satellite should follow Newton's laws[1] and move with uniform speed in an ellipse (almost a circle) around the center of the Moon. However, their measurements showed that each satellite would speed up slightly, then slow down, as it passed over one of the large circular basins on the Moon. All this first happened in 1968.

The interpretation of these accelerations is shown in Figure 2.3. According to Newton's Law of Gravitation (force $F_g = GmM/r^2$; see Pamphlet I), there must be extra mass (the mascon) in each lunar basin, which pulled the satellite toward the basin. As the satellite approached the basin, its orbital speed increased slightly; after it passed the basin, it slowed down a little. The amount of speeding up and slowing down gave an estimate of the mass concentration M. Each mascon (there are eight presently known on the Moon) is thought to be the remains of a huge meteor that hit the Moon and formed the basin (a large crater). Each mascon causes a gravity anomaly, and these were the first gravity anomalies found on an astronomical body other than the Earth. Others have since been found on Mars.

[1] Project Physics, Secs. 8.4 to 8.8; PSSC, Secs. 13-8 and 13-10. (Throughout this pamphlet, references are given to key topics covered in these three standard textbooks: "Project Physics," second edition, Holt, Rinehart and Winston, 1975; "Physical Science Study Committee" (PSSC), fourth edition, D. C. Heath, 1976; and "Investigating the Earth" (ESCP), Houghton Mifflin Company, 1973.)

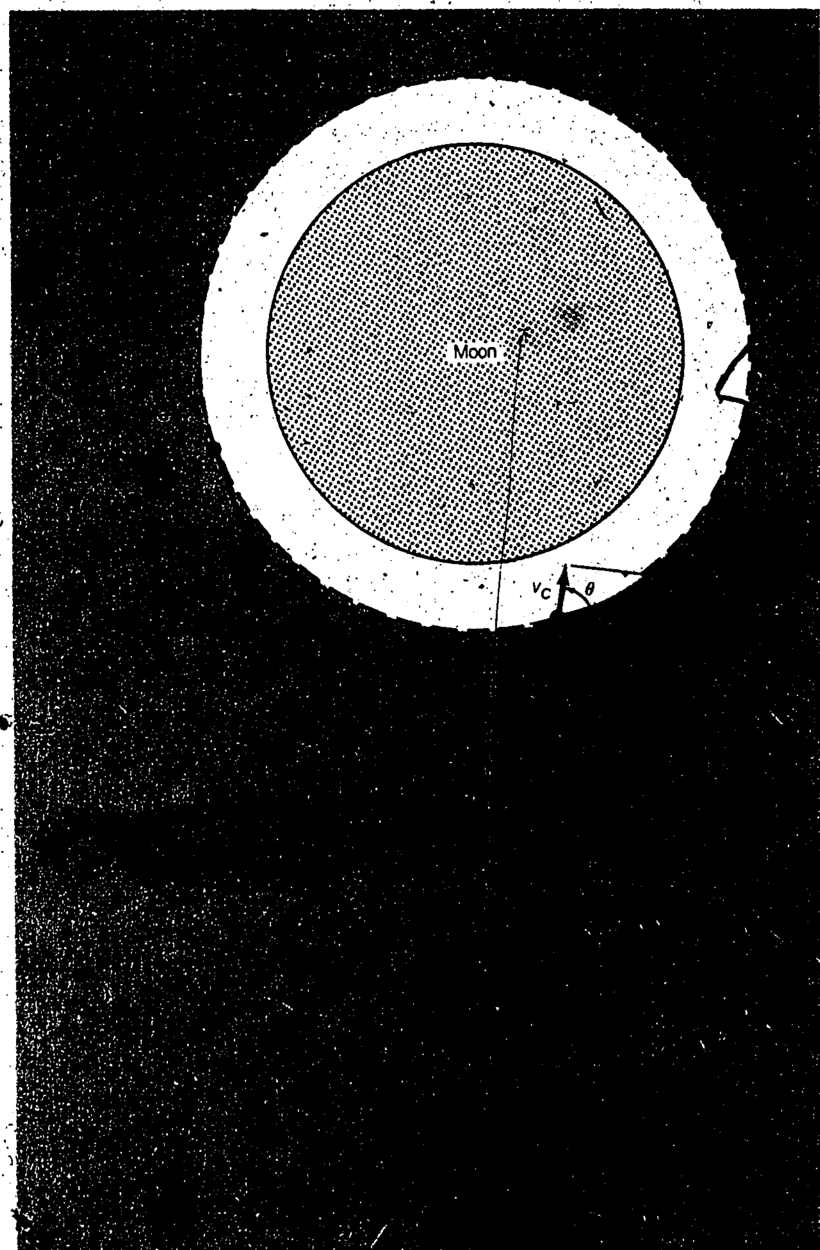

Figure 2.2 Doppler shift from the component of velocity in the line of sight.

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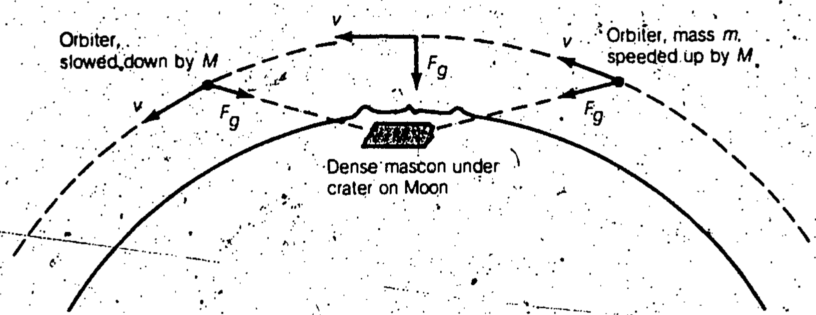
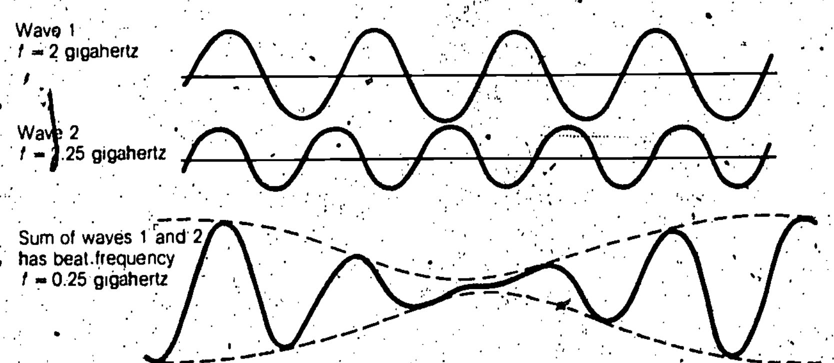
To measure the Doppler shift Δf accurately, both the broadcast frequency f and the frequency received on Earth f' must be known accurately. This is done by using crystal oscillators to control a radiofrequency electronic circuit at 2000 megahertz (2×10^9 cycles/sec) with a deviation of only a fraction of 1 hertz (1 cycle/sec). These crystal oscillators made it possible to measure the Doppler shifts on Apollo-Soyuz very accurately. The moving object (the



Effect of a mascon on the speed of a passing orbiter. **Figure 2.3**

Apollo Command Module or the Docking Module) had a crystal-controlled radio. The frequency of radio waves received was compared to the frequency of a similar crystal. The two frequencies were almost the same, but the sum of the incoming waves and the standard crystal oscillator gave a "beat frequency" equal to the difference between the two frequencies, as shown in Figure 2.4.



Beat frequency in the sum of two waves of different frequency. **Figure 2.4**

B

Questions for Discussion
(Doppler Shift)

1. The exhaust of a racing car (without a muffler) makes 10 "put-puts" per second at a speed *v* of 50 km/hr (31 mph). If the car is going away from you at that speed, how many "put-puts" will you hear each second?

2. A police car is parked on a side street at a 45° angle to the oncoming traffic on a highway. Will the Doppler radar on the police car give the correct speeds of cars on the highway?

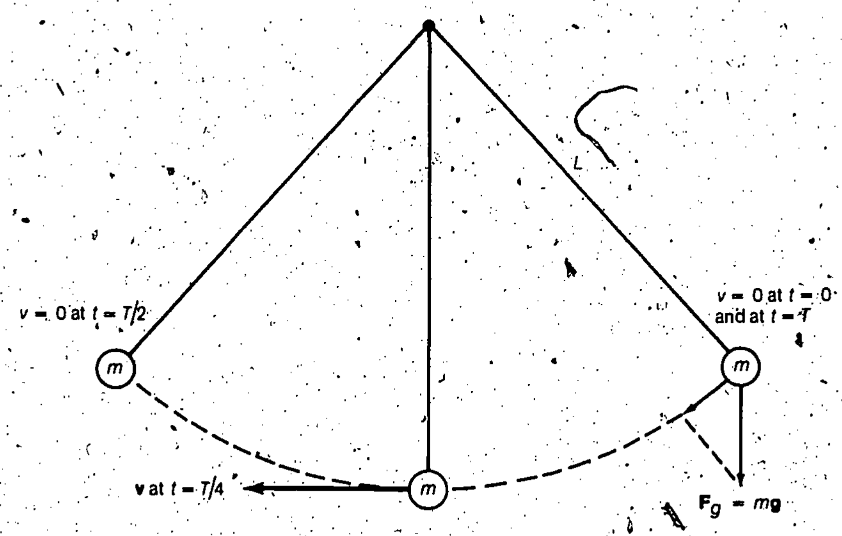
3. The lunar orbiter had an orbital speed of 1.7 km/sec. How did the Doppler shift of its 2000-megahertz radio transmitter change as it moved across the center of the Moon and rounded the edge as "seen" by a radio receiver on Earth? (Assume that there are *no* mascons.)

3 Earth's Gravity Anomalies[2]

The acceleration of gravity at the Earth's surface is called g and is about 9.8 m/sec² (see Pamphlet I). Around 1590, Galileo first measured g. About 100 years later, Newton used g and the acceleration of the Moon toward the Earth to derive his Law of Gravitation[3] ($F_g = GmM/r^2$). Much later, scientists found that g is not exactly the same everywhere on Earth. Evidently, there are high-density rocks like the lunar mascons in some places and low-density rocks in other places. Also, the Earth's rotation reduces g from 9.83 m/sec² near the poles to 9.78 m/sec² near the Equator. The rotation also changes the shape of the Earth, producing a bulge near the Equator where the diameter is 43 kilometers more than the diameter through the poles.

A Gravity Meters[4]

Early measurements of g were made by timing the swing of a pendulum (Fig. 3.1). The period T of a pendulum's swing is $2\pi\sqrt{L/g}$, where L is the length of the pendulum. So, $g = 4\pi^2 L/T^2$. The period can be measured very accurately by counting 10 000 swings and dividing the total time by 10 000.



A pendulum used to measure g from $4\pi^2 L/T^2$. **Figure 3.1**

[2]ESCP, Sec. 3-10.
[3]Project Physics, Secs. 8.4 to 8.8; PSSC, Secs. 13-8 and 13-10.
[4]Project Physics, Problem 8.19; PSSC, Sec. 13-10.

If you have a stopwatch that is accurate to 0.1 second, your value of T is good to ±0.00001 second.

An accurate pendulum is still the best instrument to measure g, and such measurements have been made at hundreds of geophysical stations all over the world. However, a pendulum won't work on a rolling ship or in an airplane flying through bumpy air. Scientists therefore produced a "gravimeter," which has a small mass m on a spring (Fig. 3.2). The force of gravity on m is $F_g = mg$. If g is slightly larger, the spring is stretched slightly farther. Gravimeters have complex ways of magnifying this extra stretch.

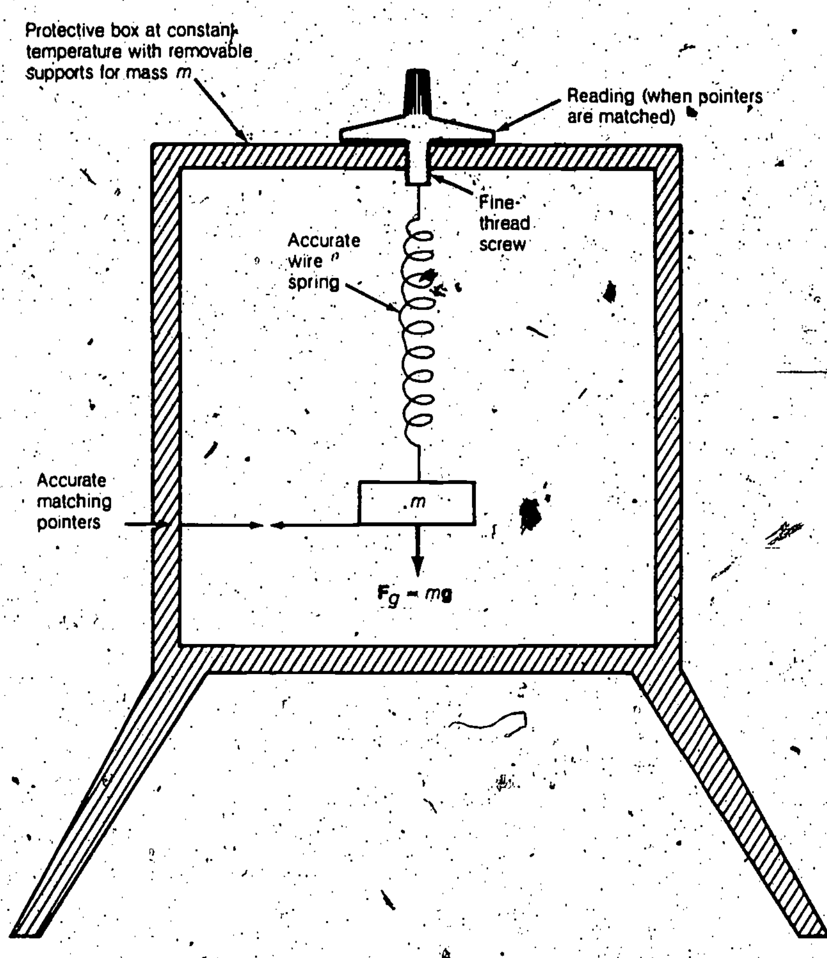


Figure 3.2 A gravimeter for measuring g by the extension of an accurate spring.

Some use bent quartz fibers as part of the spring, and the instrument is protected from careless handling and temperature changes that might affect the readings. Each gravimeter is calibrated against a standard pendulum just before it is used. A good gravimeter can measure g with an error of less than 0.1 mm/sec^2.

B Gravity Anomalies and Earth Structure

Geologists on foot have carried gravimeters into mountains and across plains. They have taken them along seacoasts in automobiles and out into oceans in submarines. In some places, they have made surveys while flying in airplanes at constant altitude. The acceleration of gravity g is slightly smaller at higher altitudes because the distance from the center of the Earth is greater. The force of gravity is proportional to $1/r^2$, where r is the distance from the Earth's center. Gravity readings are usually corrected to what they would be at sea level.

Maps of g corrected to sea level show many maximums and minimums; that is, humps and troughs in the force of gravity. If the Earth were perfectly homogeneous, there would be no maximums and no minimums. The measured values thus tell geologists about the *structure* of the Earth's crust. In general, g is higher over continents where dense rocks are near the surface and lower over deep ocean basins where the dense rocks are far below. Other smaller structures, such as iron-ore, coal, oil, and salt deposits, can be detected. Caves and underground lava flows can also be located. Gravimeter surveys are useful in prospecting for oil. They also indicate the shape of buried craters and extinct volcanoes.

Gravimeter surveys by foot, automobile, or submarine are slow but relatively accurate. Measurements from airplanes, although faster, tend to be inaccurate. Measurements of g from satellites have the advantage of covering very large areas in a short time. A primary objective of the gravity experiments during the Apollo-Soyuz mission was to determine how accurate the measurements from a satellite would be. Of course, a gravimeter cannot be used in a spacecraft in orbit because everything there is weightless and g would be measured as zero. (The spring would pull the mass m to the top of the box in Figure 3.2 because $F_g = 0$; see Pamphlet I.) The method used depends on the *accelerations of the spacecraft* (as in the discovery of mascons on the Moon). Because Apollo-Soyuz was in a low (222-kilometer altitude) circular orbit, small changes in g at the Earth's surface could be detected. A higher satellite would be less sensitive to changes in g.

C. Questions for Discussion

(Gravimeters, Gravity Anomalies)

4. An old-fashioned pendulum clock keeps accurate time at sea level, but the owner moves it to a hotel on Pike's Peak, at an altitude of about 4 kilometers (14 000 feet). Will it run fast or slow?

5. When an airplane goes into a banked turn, what happens to the reading of a gravimeter onboard the airplane?

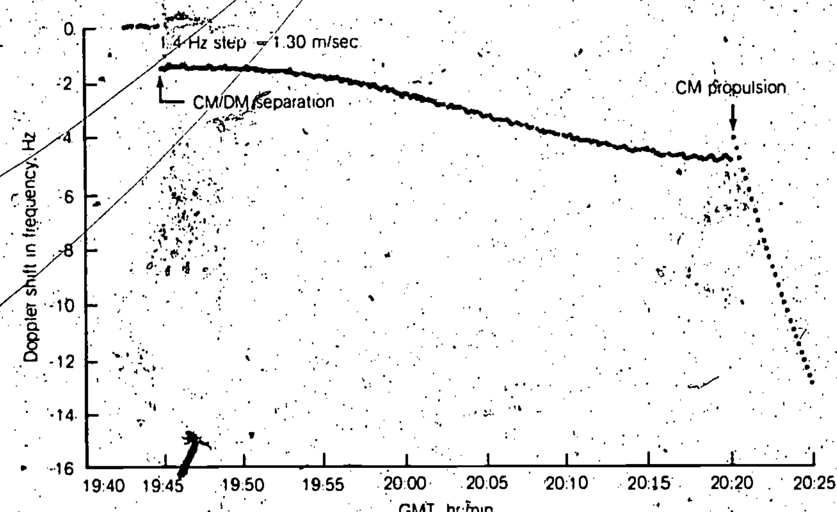
6. If g is 9.8000 m/sec^2 on the surface in the Midwestern United States, what is it at an altitude of 12 kilometers (39 000 feet)? (The radius of the Earth is 6378 kilometers.)

7. How does the Earth's rotation reduce g near the Equator?

4 The "Low-Low" Satellite Technique

When two satellites in low orbit follow one another past a gravity anomaly, the first is speeded up before the second one is and the distance between them increases. Then the first satellite is slowed down (back to normal) before the second one is and the distance between them decreases (Fig. 4.1). The MA-089 Doppler Tracking Experiment was designed to detect these changes in distance. A crystal-controlled radio transmitter was mounted on the Docking Module (DM), and a receiver with a similar crystal was placed on the Apollo Command Module (CM). Each weighed about 7 kilograms. While the DM was attached to the CM, the radios were warmed up and tested for constant frequency. This test showed a slight change of about 3 parts in 10^{12}; that is, the broadcast frequency of 324 megahertz (324 million cycles/sec) varied by only 1 millihertz (0.001 cycle/sec).

On July 23 at 19:45 Greenwich mean time (GMT—the time in Greenwich, England, used as standard time on the Apollo-Soyuz mission), the DM was unlatched from the Apollo CM. Before releasing the DM, the astronauts used the Apollo reaction-control jets to spin Apollo and the DM at about one rotation every 72 seconds. After the DM was released, the Apollo CM gradually ceased spinning and backed away from the DM. The purpose of the DM rotation was to stabilize it with its radio antenna toward Apollo. Although this approach worked fairly well, the DM still had a small wobble that brought its antenna first toward and then away from Apollo. This wobble



Doppler shift of the 324-megahertz frequency showing the DM drift after separation and the CM rocket firing. **Figure 4.1**

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introduced an unwanted but small periodic Doppler shift in the DM radio transmission.

The Doppler shift as Apollo backed away from the DM at 1.3 m/sec is shown in Figure 4.1. At 20:20 GMT, the Apollo reaction jets were fired to separate the Apollo from the DM more quickly. When they reached 300 kilometers, the astronauts fired the jets in the other direction so that Apollo stayed about the same distance behind the DM.

Although the radio receiver could measure the difference in frequency accurately, there were three anticipated complications in measuring the accelerations caused by gravity anomalies. First, the DM moved into a slightly different orbit from that of the CM. This change in orbital shape caused a periodic increase and decrease of the separation every 93 minutes, the time for one trip around the Earth (see Fig. 4.2 and Pamphlet I). Second, atmospheric drag on the two orbiters was slightly different, which caused a gradual increase in separation. Finally, electrons in the Earth's upper atmosphere between the two orbiters caused a small shift in the frequency of the radio transmissions.

The slight difference in orbit was checked by ground observations so that corrections could be made. The atmospheric drag was estimated in advance (it caused a smooth, long-term change in separation). After correcting for this, short-term changes due to gravity anomalies could still be detected. The effect of electrons could be measured by using *two frequencies*, 162 and 324 megahertz. The electrons changed one frequency more than the other, so both the Doppler shift and the shift due to electrons could be calculated from the two measured frequency changes.

The frequency shifts were measured over 10-second intervals for 13.8 hours as the DM and the CM circled the Earth nine times. During these nine orbits, they passed over various parts of the Earth's surface and should have recorded many gravity anomalies. However, unlike the tests made when the

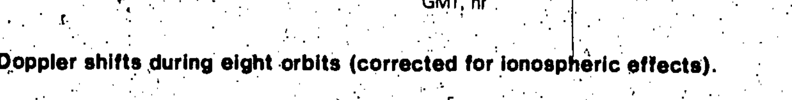
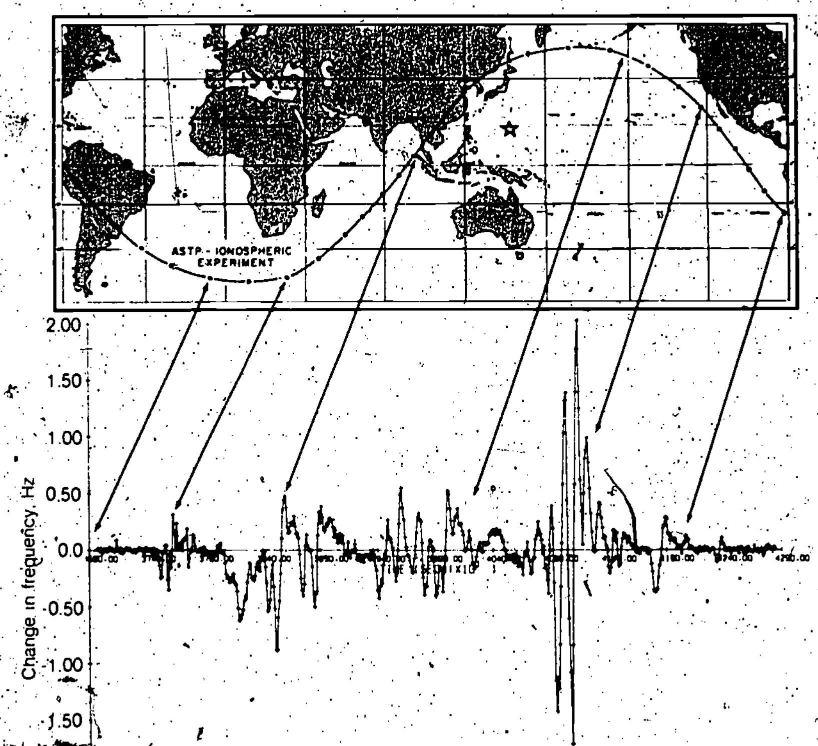


Figure 4.2 Doppler shifts during eight orbits (corrected for ionospheric effects).

CM and DM were still connected, variations in the DM radio-signal strength were so large during the actual experiment that the CM receiver could not measure the Doppler shift accurately. Because of these difficulties, the "low-low" technique detected no gravity anomalies during the Apollo-Soyuz flight, but another attempt on some future mission may be successful.

Nevertheless, the MA-089 Experiment was able to measure the ionization of the low-density atmosphere at a 222-kilometer altitude. The electron density varied from 3×10^9 electrons/m^3 on the nightside of the Earth to 5×10^{11} electrons/m^3 on the dayside. More interesting were the many sudden changes in ionization. Most of these occurred as Apollo-Soyuz crossed the Equator, which indicates that the ionosphere (see Pamphlet V) is irregular in that region. Figure 4.3 is a plot of the change of frequency during



Map of revolution 127 with plot of MA-089 frequency changes. The electron density between the Apollo CM and the DM can be computed from the change in frequency. **Figure 4.3**

one revolution (number 127). This plot shows a big "wave" due to changes in electron density just west of California on the evening of July 23, 1975. This wave had a wavelength of 690 kilometers over which the electron density changed by 35 percent. The wave extended 7200 kilometers along the Apollo-Soyuz orbit.

5 The "High-Low" Satellite Technique

A satellite at very high altitude is almost unaffected by gravity anomalies because of the $1/r^2$ in Newton's Law of Gravitation. Therefore, Doppler tracking of a low satellite (accelerated by gravity anomalies) from a high satellite should make measurements of those accelerations possible. The situation is complicated because the low satellite (Apollo) moves at changing angles to the high-low line (Fig. 5.1). When Apollo was directly under the high satellite, there was no Doppler shift because there was no component of orbital velocity along the high-low line.

The ATS-6 Geosynchronous Satellite

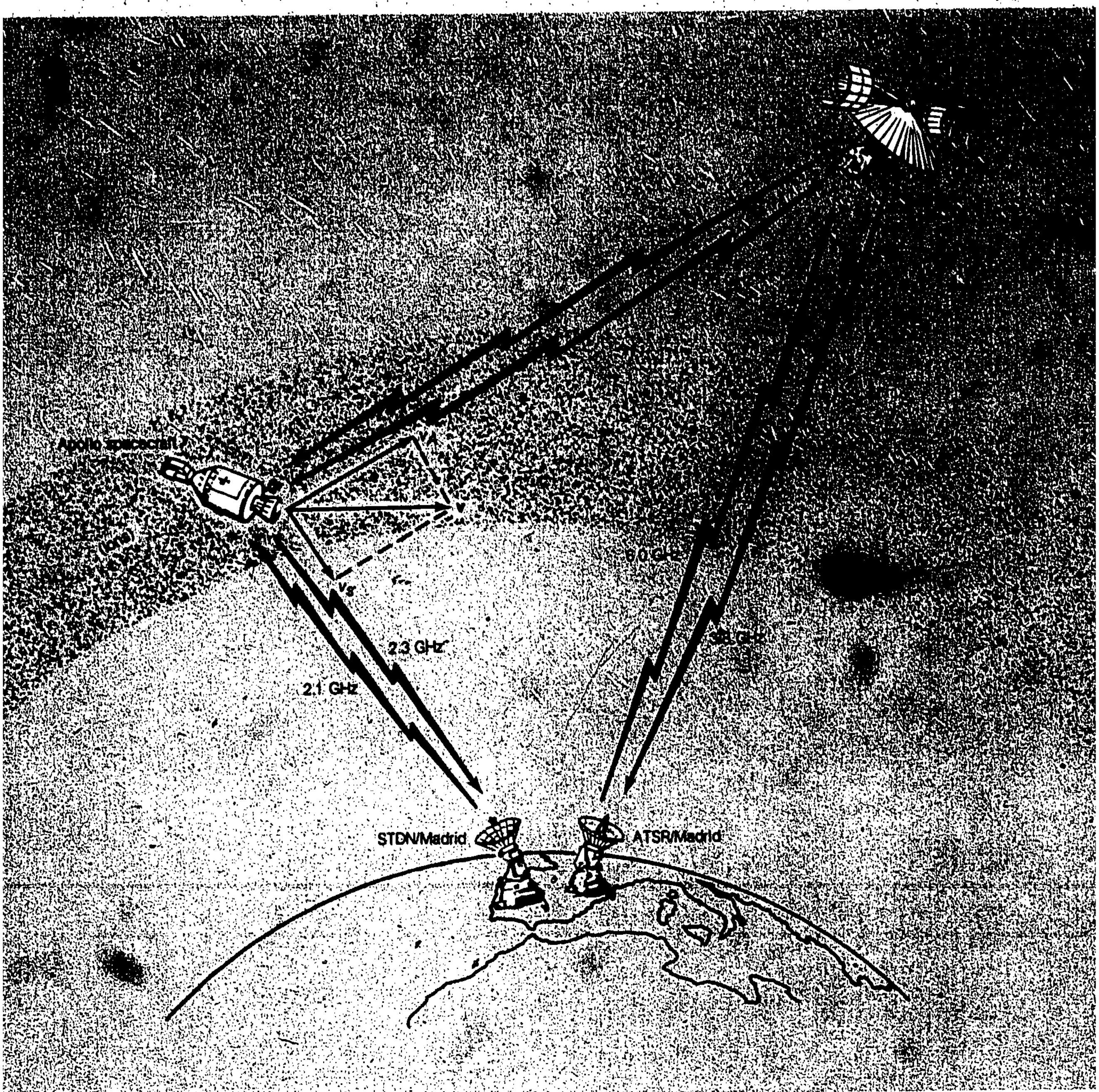
The ATS-6 communications satellite was in a 24-hour geosynchronous orbit 35 900 kilometers above Lake Victoria in East Africa. At that height, 42 280 kilometers from the Earth's center, it circles the Earth every 24 hours and remains over the same point on the Equator all the time (hence the name geosynchronous—"in time with the Earth"). The ATS-6 satellite was located in this position to broadcast television programs to India and Africa, and it was also used for communications with Apollo-Soyuz (see Pamphlet I). It relayed voice, radio, and television communications on several circuits to the ATS receiver in Madrid, Spain. NASA has several other ATS satellites planned that will eventually relay "real-time" television and radio transmissions to or from any part of the world.

The STDN receiver-transmitter at Madrid (Fig. 5.1) is part of NASA's worldwide *S*pacecraft *T*racking and *D*ata *N*etwork of 17 ground stations and several ships. When Apollo-Soyuz was 5° above the local horizon, each of these radio stations could relay messages to or from Apollo and Soyuz.

The Apollo spacecraft in low Earth orbit, the ATS-6 satellite in high orbit (actually more than 160 times higher than Apollo), and the ground receivers at Madrid, Spain, are shown schematically in Figure 5.1. The radio frequencies used between each pair are given in gigahertz (10^9 cycles/sec). The 2.25-gigahertz radio signals from Apollo to ATS-6 have a Doppler shift of $\Delta f = 2.25 \times 10^9 \, v_A/c$, where v_A is the *component* of Apollo's orbital velocity v along the Apollo/ATS-6 line. The Doppler shift (and v_A) was zero when Apollo passed directly under the ATS-6 and v was perpendicular to the line from Apollo to ATS-6. The shift was a maximum (v_A almost equal to v) when Apollo was near the horizon as seen from the ATS-6. These Doppler-shifted signals were then radioed to the ATS receiver in Madrid on a 3.8-gigahertz circuit with almost no Doppler shift because the position of the ATS-6 is nearly fixed in the sky.

It would also have been possible to measure the Doppler shift in the Apollo 2.3-gigahertz radio transmissions to the STDN station in Madrid

Figure 5.1 Schematic of the ATS-6/Apollo communication links. The ATS Ranging station is designated ATSR; the NASA Spacecraft Tracking and Data Network station is designated STDN.



($\Delta f = 2.3 \times 10^8 v_s/c$), but the effect of ions in the lower atmosphere complicates such measurements (see Sec. 4). Ions had little effect on the Apollo/ATS-6 link or on the ATS-6/Madrid link because these radio waves travel only short distances through the ions, and a small correction could be made for the ion effect.

B The MA-128 Geodynamic Experiment

The objective of the Geodynamic Experiment was to measure gravity anomalies as small as 0.05 mm/sec² over features as small as 300 kilometers. Two areas were selected: the center of Africa, which has positive gravity anomalies, and the Indian Ocean trough, which has a negative gravity anomaly. Apollo passed over central Africa on its 115th orbit (revolution) around the Earth and over the Indian Ocean on revolutions 8, 23, and 53, as shown in Figure 5.2. Measurements were made on these orbits and on revolutions 120 and 135. Gravity anomalies were measured in the three areas shown in Figure 5.2. Because the ATS-6 satellite was almost directly overhead in Africa, the component v_A in Figure 5.1 was directed nearly up or down over each anomaly (as over the mascon in Fig. 2.3), and the sensitivity for measuring the strength of the anomaly was high.

The radiofrequency crystal oscillators were stable enough that velocity changes as small as 1 mm/sec were detected. Errors in the measured values of v_A were about 0.5 mm/sec. Measurements were made on 108 orbits for the 40 minutes of each 93-minute orbital period during which Apollo was within 7500 kilometers of the point in East Africa directly under the ATS-6. (During the other 53 minutes of each orbit, Apollo either couldn't see the ATS-6 or saw it so near the horizon that many ions were in the line of sight.) When Apollo was rolled or turned in any way, its radio antenna was moved artificially. The time of such maneuvers was recorded at the Mission Control Center (MCC) at the NASA Lyndon B. Johnson Space Center (JSC) in Houston. The MA-128 Doppler measurements at those times were no good (the scientists didn't want to misinterpret a spacecraft roll as a gravity anomaly!). In general, two or more orbits over the same gravity anomaly were used to estimate its strength.

C Results of the Geodynamic Experiment

Changes in v_A (the component of Apollo's orbital velocity toward the ATS-6) during three orbits over the Indian Ocean and the Himalaya Mountains are shown in Figure 5.3. After correction for the effects of ions and electrons between Apollo and the ATS-6, the Doppler shifts (Δv_A) definitely show the

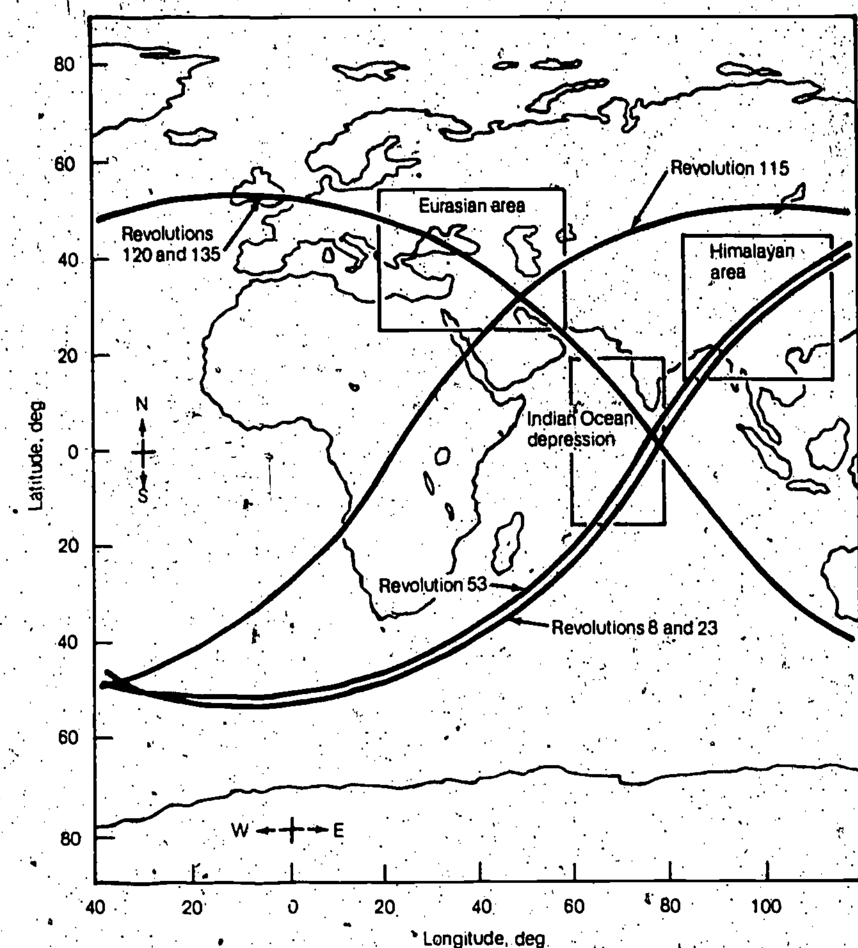
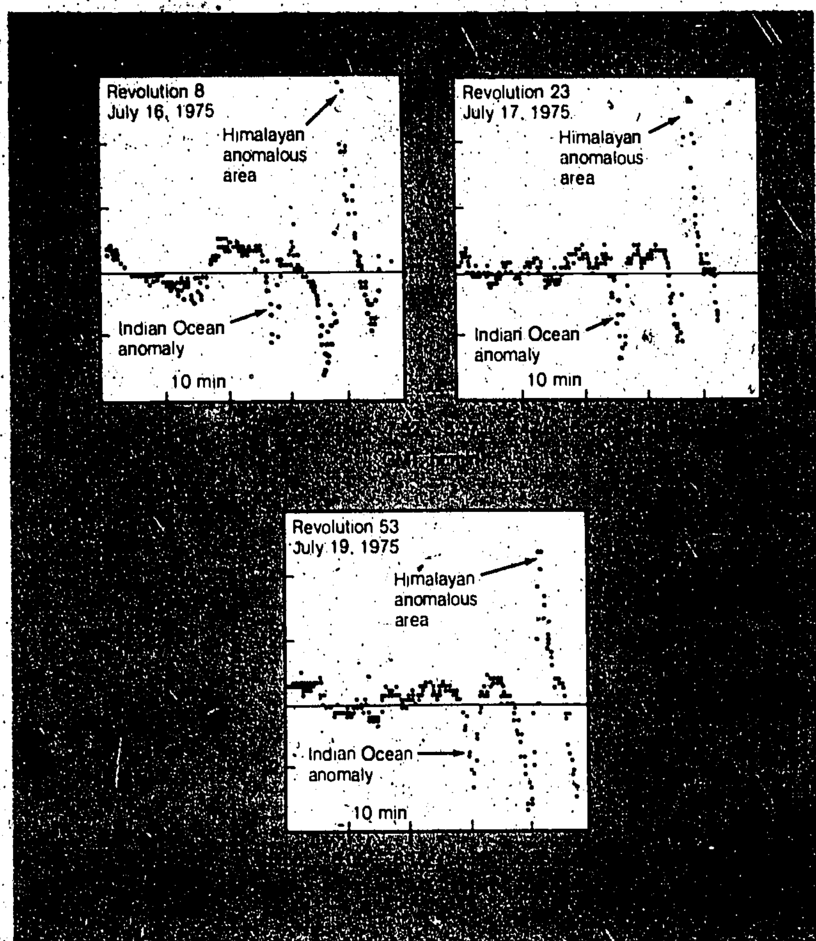


Figure 5.2 **Apollo spacecraft groundtracks for Experiment MA-128.**

Indian Ocean anomaly. The Himalayan anomaly is less certain, however, because there was a high density of atmospheric ions over the Himalayas each time Apollo passed over. If the changes in v_A are converted to the strength of the anomalies, the two largest anomalies correspond to changes in g of 0.6 and 1.0 mm/sec², about 10^{-4} g. Other orbits showed 10^{-5}-g anomalies in Asia Minor, 10^{-6}-g anomalies in central Africa, and less well determined anomalies in the Southern Hemisphere. Some of the anomalies in Asia Minor are associated with continental drift (movement of large sections of the Earth's crust) in that area (see Pamphlet V).



Changes in Apollo velocity toward the ATS-6 caused by gravity anomalies in the Indian Ocean and Himalaya Mountains. Note that v_A changes agree well on three orbits. **Figure 5.3**

The MA-128 Experiment also provided new data about the Earth's atmosphere. Measurements made just as Apollo disappeared from ATS-6 view below the horizon (or as Apollo reappeared above the horizon) show the refraction (bending) of radio waves in the Earth's atmosphere. These refractions can be used to derive the temperature T and the pressure P of the atmosphere through which the radio waves passed. Using measurements taken at 1-second intervals for 30 seconds before Apollo disappeared below or after it reappeared above the horizon, the scientists derived T and P for several altitudes. In one place, the values derived agree with measurements made from a balloon flight, which means that the "high-low" satellite combination can collect certain meteorological (weather) data rapidly. Later, when satellites are positioned at several longitudes around the world, this technique will give measurements of T and P wherever low satellites cross a ring about 9000 kilometers from the point under each high satellite.

D Questions for Discussion

(Doppler Effect, Spin, Orbits)

8. With crystal oscillators controlling radiofrequency to 1 millihertz in 334 megahertz, what is the smallest velocity along the line of sight that can be detected?

9. If the DM had not been stabilized by a spin, what could have happened to prevent collection of the Apollo-DM Doppler measurements?

10. If the Earth rotated once every 12 hours (instead of once every 24 hours), how high would a geosynchronous satellite have to be?

11. Figure 5.1 shows an intermediate position of Apollo relative to the ATS-6. Where would the Doppler shift be at a maximum? Where would Apollo be for zero Doppler shift?

Appendix A

Discussion Topics (Answers to Questions)

1. (Sec. 2B) The Doppler formula is $\Delta f = fv/v_S$. The "put-put" frequency f is 10 put-puts/sec. The speed of the car v is 50 km/hr or 13.9 m/sec. The speed of sound v_S is 320 m/sec. Therefore, $\Delta f = (10)(13.9/320) = 0.434$ put-puts/sec, and $f' = f - \Delta f = 9.566$ put-puts/sec.

2. (Sec. 2B) The Doppler radar on the police car will detect only the component of a car's velocity in its line of sight, 45° to the highway (car's velocity v). It will thus read $v \cos 45°$, or $0.707\ v$.

3. (Sec. 2B) At the center of the Moon as seen from Earth, the orbiter is moving across our line of sight ($\theta = 90°$ in Fig. 2.2); therefore, the Doppler shift is zero. At the edge of the Moon, the orbiter is moving directly away from us ($\theta = 180°$), and $v_c = -v = 1.7$-km/sec recession. The Doppler shift is then $\Delta f = -fv/c = -2 \times 10^9 (1.7/3 \times 10^5) = -1.13 \times 10^4$ hertz or -11.3 kilohertz (-11.3 kilocycles/sec red shift).

4. (Sec. 3C) The period of a pendulum swing $T = 2\pi\sqrt{L/g}$. At sea level, $g = 9.80$ m/sec²; at a 4-kilometer (14 000 foot) altitude (4 kilometers farther from the Earth's center), g is smaller (9.786 m/sec²), so T would be larger. The ratio of T on the mountain to T at sea level is $\sqrt{9.80/9.786} = \sqrt{1.0014} = 1.0007$. The period is thus 0.0007 longer on the mountain, and the clock runs slow by (0.0007)(1440 min/day) = 1.0 min/day.

5. (Sec. 3C) The airplane in a banked turn is accelerated toward the center of its turn, and this acceleration increases the gravimeter reading.

6. (Sec. 3C) By Newton's Law of Gravitation, $F_g = GMm/r^2 = mg$. Thus, g is proportional to $1/r^2$, where r is the distance from the Earth's center. At a 12-kilometer altitude, r is 6390, and g at that altitude is $(6378\text{ km}/6390\text{ km})^2 = 0.9962$ times g at sea level, or $(0.9962)(9.8000) = 9.763$ m/sec².

7. (Sec. 3C) At the Equator, a mass is moving at $v = 460$ m/sec in a circle with a radius r of 6378 kilometers as the Earth rotates once every 24 hours. Part of the gravitational force $F_g = GmM_E/r^2$ is used to keep m moving in this circle at acceleration $a = v^2/r$. Therefore, a spring balance or gravimeter records $F_g - mv^2/r = mg - ma$; and g is reduced by $a = v^2/r$. "Centrifugal force" is the term used to describe mv^2/r.

8. (Sec. 5D) In the Doppler formula $\Delta f = fv/c$, we need Δf larger than 1 millihertz. So v must be larger than (1 millihertz/f) c, or $(10^{-3}/3.34 \times 10^8)(3 \times 10^8\text{ m/sec}) = 9 \times 10^{-4}$ m/sec, or 9×10^{-1} mm/sec, or 0.9 mm/sec.

9. (Sec. 5D) If the DM had not been stabilized, it would probably have "tumbled" so that its transmitting antenna faced away from Apollo. In that case, no radio signals could have been received by Apollo.

10. (Sec. 5D) The period T of a satellite is related to its distance r from the Earth's center by Kepler's Law (see Pamphlet I): T^2 is proportional to r^3. If T is reduced from 24 hours to 12 hours, r^3 must be reduced by $(24/12)^2 = 4$. The altitude of the geosynchronous orbit, 35 900 kilometers, plus the radius of the Earth, 6378 km = 42 278 = r. Therefore, the new $r^3 = (1/4)(42\ 278)^3 = (1/4)(7.56 \times 10^{13}) = 1.89 \times 10^{13}$, and $r = 2.66 \times 10^4$ kilometers, or 26 600 kilometers from Earth's center, or 20 200 kilometers above the Equator.

11. (Sec. 5D) The Apollo's Doppler shift would be a maximum when its orbital velocity v was along the Apollo/ATS line of sight, at the lower left in Figure 5.1. The Doppler shift would be zero when Apollo passed under ATS-6 as it moved across the line of sight.

Appendix B

SI Units

Powers of 10

International System (SI) Units

Names, symbols, and conversion factors of SI units used in these pamphlets:

Quantity	Name of unit	Symbol	Conversion factor
Distance	meter	m	1 km = 0.621 mile 1 m = 3.28 ft 1 cm = 0.394 in. 1 mm = 0.039 in. 1 μm = 3.9×10^{-5} in. = 10^4 Å 1 nm = 10 Å
Mass	kilogram	kg	1 tonne = 1.102 tons 1 kg = 2.20 lb 1 gm = 0.0022 lb = 0.035 oz 1 mg = 2.20×10^{-6} lb = 3.5×10^{-5} oz
Time	second	sec	1 yr = 3.156×10^7 sec 1 day = 8.64×10^4 sec 1 hr = 3600 sec
Temperature	kelvin	K	273 K = 0° C = 32° F 373 K = 100° C = 212° F
Area	square meter	m^2	1 m^2 = 10^4 cm^2 = 10.8 ft^2
Volume	cubic meter	m^3	1 m^3 = 10^6 cm^3 = 35 ft^3
Frequency	hertz	Hz	1 Hz = 1 cycle/sec 1 kHz = 1000 cycles/sec 1 MHz = 10^6 cycles/sec
Density	kilogram per cubic meter	kg/m^3	1 kg/m^3 = 0.001 gm/cm^3 1 gm/cm^3 = density of water
Speed, velocity	meter per second	m/sec	1 m/sec = 3.28 ft/sec 1 km/sec = 2240 mi/hr
Force	newton	N	1 N = 10^5 dynes = 0.224 lbf

Quantity	Name of unit	Symbol	Conversion factor
Pressure	newton per square meter	N/m^2	$1\ N/m^2 = 1.45 \times 10^{-4}\ lb/in^2$
Energy	joule	J	1 J = 0.239 calorie
Photon energy	electronvolt	eV	$1\ eV = 1.60 \times 10^{-19}\ J$; $1\ J = 10^7\ erg$
Power	watt	W	1 W = 1 J/sec
Atomic mass	atomic mass unit	amu	$1\ amu = 1.66 \times 10^{-27}\ kg$

Customary Units Used With the SI Units

Quantity	Name of unit	Symbol	Conversion factor
Wavelength of light	angstrom	Å	$1\ Å = 0.1\ nm = 10^{-10}\ m$
Acceleration of gravity	g	g	$1\ g = 9.8\ m/sec^2$

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Unit Prefixes

Prefix	Abbreviation	Factor by which unit is multiplied
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Powers of 10

Increasing	Decreasing
$10^{2} = 100$	$10^{-2} = 1/100 = 0.01$
$10^{3} = 1\ 000$	$10^{-3} = 1/1000 = 0.001$
$10^{4} = 10\ 000$, etc.	$10^{-4} = 1/10\ 000 = 0.000\ 1$, etc.
Examples:	Example:
$2 \times 10^{6} = 2\ 000\ 000$	$5.67 \times 10^{-5} = 0.000\ 056\ 7$
$2 \times 10^{30} = 2$ followed by 30 zeros	

Appendix C

Glossary

References to sections, Appendix A (answers to questions), and figures are included in the entries. Those in *italic* type are the most helpful.

acceleration (a) change of velocity with time. (Secs. 2A, 3, 4; App. A, nos. 5, 7; Figs. 2.3, 5.3) The acceleration of gravity at the Earth's surface is called g.

ATS-6 communications satellite a satellite in geosynchronous (24-hour period) orbit 35 900 kilometers above East Africa, used to rebroadcast radio signals to and from the control station in Madrid, Spain. (Secs. 1, *5A*, 5B, 5C; App. A, no. 11; Figs. 5.1, 5.3)

basin a depression. Basins on the Moon are large craters caused by meteor impact. Ocean basins on Earth are deep places in the floor of the oceans. (Secs. 2A, 3B)

beat frequency when two sources are emitting sound waves of a different frequency (f_1, f_2), the combined sound swells and falls in intensity, producing *beats*. The frequency of the beats is $f_2 - f_1$. (Sec. 2A; Fig. 2.4)

c the velocity of light, radio, and other electromagnetic waves, 3×10^8 m/sec. (Sec. 2)

Command Module (CM) the part of the Apollo spacecraft in which the astronauts lived and worked; attached to the Service Module (SM) until reentry into the Earth's atmosphere. (Sec. 4; Fig. 4.3)

component (radial) of velocity the fraction of a velocity vector that is along the line of sight of an observer; it is only this fraction that produces Doppler shift. (Secs. *2A*, 5 to 5C; App. A, nos. 2, 3, 11; Figs. *2.2*, 5.1, 5.3)

crater a circular depression. Most of those on the Moon were produced by meteor impact. (Secs. 2A, 3B; Fig. 2.3)

crystal a solid composed of atoms or ions or molecules arranged in a regular repetitive pattern. In an electronic circuit, it oscillates with a fixed frequency. (Secs. 2A, 4, 5B; App. A, no. 8)

Docking Module (DM) a special component added to the Apollo spacecraft so that it could be joined with Soyuz. (Secs. 1, 4; App. A, no. 9; Figs. 4.1, 4.3) See Pamphlet I.

Doppler shift the change of frequency and wavelength in the spectrum of a source approaching an observer (blue shift) or receding from him (red shift). (Secs. *2*, 2A, 4, 5 to 5C; App. A, nos. 1 to 3, 8, 11; Figs. 2.1, 2.2, 4.1, 4.2)

drag, atmospheric the frictional forces opposing spacecraft velocity, caused even at high altitudes by the low-density Earth atmosphere there. Atmospheric drag lowers the orbit. (Sec. 4)

frequency (f) the number of oscillations or waves leaving a sound source or a radio antenna or a light source per second. (Secs. 2, 2A, 4, 5A, 5B; Figs. 2.4, 4.3)

g acceleration of gravity at the Earth's surface, 9.8 m/sec^2. (Secs. 1, *3*, 3A to 3C, 5C; App. A, nos. 4, 6, 7; Figs. 3.1, 3.2)

geosynchronous orbit an orbit that is synchronized with the Earth's rotation. A satellite that is 35 900 kilometers above the Equator (42 400 kilometers from the Earth's center) and that is moving eastward has a 24-hour orbit and remains over the same place on Earth. (Sec. 5A; App. A, no. 10)

gravimeter an instrument for measuring *g* by the extension of a spring. (Secs. *3A*, 3B; App. A, nos. 5, 7; Fig. 3.2)

gravitation the force of attraction between two masses (*m* and *M*), given by Newton's Law $F_g = GmM/r^2$, where *r* is the distance between them and *G* is a constant. (Secs. 2A, 3, *5*; App. A, nos. 6, 7)

gravity the downward force on a mass near the Earth. (Secs. 3 to 3B)

gravity anomaly a region where gravity is lower or higher than expected if the Earth's crust is considered to have uniform density. (Secs. *1*, 2A, 3, 3B, 4, 5, 5B, 5C)

Greenwich mean time (GMT) the time of an event, from 0 at midnight to 12 hours at noon to 24 hours at midnight, as measured at 0° longitude (Greenwich, near London, England). GMT is used on space missions to avoid confusion with other time zones. See Pamphlet I.

groundtrack the path followed by a spacecraft over the Earth's surface. (Fig. 5.2)

hertz (Hz) a unit of frequency, one oscillation (cycle) per second: 1 millihertz = 10^{-3} cycles/sec, 1 kilohertz = 1000 cycles/sec, 1 megahertz = 10^6 cycles/sec, 1 gigahertz = 10^9 cycles/sec.

high-low a technique for measuring gravity anomalies, using one high-orbit satellite and one low-orbit satellite and measuring radio Doppler shifts between them. (Secs. 1, *5*, 5A to 5C)

ion an atom with one or more electrons removed or, more rarely, added. The electrons along the path of a radio wave change its frequency. Ionization is the fraction of atoms ionized. (Secs. 4, 5A, 5C; Figs. 4.2, 5.1)

low-low a technique for measuring gravity anomalies, using two satellites in low orbit and measuring radio Doppler shifts between them. (Secs. 1, *4*)

MA-089 the Doppler Tracking Experiment on the Apollo-Soyuz mission. (Secs. 1, *4*; Fig. 4.3)

MA-128 the Geodynamics Experiment. (Secs. 1, *5B*, 5C)

mascon *mass con*centration; a region of high density below the Moon's surface. (Secs. *2A*, 3, 3B, 5B; Fig. 2.3)

orbit the path followed by a satellite around an astronomical body such as the Earth or Moon. (Secs. 1, 2A, 3B, 4, 5A to 5C; Figs. 4.2, 5.3) The orbit number or "revolution" was used on Apollo-Soyuz to identify the time. (Sec. 5B; Figs. 4.3, 5.2)

oscillator an electronic device producing radio waves of a given frequency. *Crystal* oscillators give a highly accurate frequency. (Secs. 2A, 5B; App. A, no. 8)

pendulum a mass suspended from a fixed point so that it can swing back and forth freely. (Sec. *3A*; App. A, no. 4; Fig. *3.1*)

period (*T*) the time taken by a satellite to travel once around its orbit, or the time between two successive swings of a pendulum or between two successive wave crests in radio or light waves. (Secs. 2, 3A; App. A, nos. 4, 10; Fig. 2.1)

r the distance of a satellite from the Earth's center.

radio waves electromagnetic waves of wavelength between 1 millimeter and several thousand kilometers and frequencies between 300 gigahertz and a few hertz. The higher frequencies are used for spacecraft communications, the lower for Navy communications. (Secs. 2, 2A, 4, 5A to 5C; App. A, no. 9)

reaction-control jets small propulsion units on a spacecraft used to rotate it or to accelerate it in a specific direction. (Sec. 4)

refraction the bending of electromagnetic rays such as light or radio waves where the material they are passing through changes in density or other properties. (Sec. 5C)

revolution the revolution or orbit number of a spacecraft in orbit around the Earth. (Sec. 5B; Figs. 4.3, 5.2)

Service Module (SM) the large part of the Apollo spacecraft that contains support equipment; it is attached to the Command Module (CM) until just before the CM reenters the Earth's atmosphere.

sound waves pressure oscillations in the air. The speed of sound is 320 m/sec. (Sec. *2*; App. A, no. 1; Fig. 2.1)

vector a directed quantity, such as velocity, force, or acceleration. Vector symbols (**v**, **F**, **a**) are given in **boldface** type.

wavelength (λ) the distance from the crest of one wave to the crest of the next, usually measured in angstroms for x-rays and visible light and in centimeters or meters for radio waves—see Appendix B. (Sec. 2)

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