9.3: Local Moving Orders for Mass

moving orders front the local commander, spacetime!

Navigation satellites near Earth drift away from "perfect" orbits because thin air and solar radiation pressure affect their motion. Figure 9.3.1 shows an experimental satellite that carries a "conscience" designed to assure that the same motion will be maintained when it encounters these disturbances as when it moves through perfect emptiness. The "conscience" - called a proof mass - is a separate sphere that floats inside the larger ship. The proof mass undergoes no acceleration relative to the ship as long as the ship moves freely. When relative motion does occur, the error in the tracking must be due to the satellite. By small rockets the satellite gives itself a brief spurt of acceleration and comes back into step with the inner proof mass - the satellite's conscience. Though resistance is present, the rocket thrust overcomes it. The satellite takes the same course it would have taken had both resistance and thrust been absent.

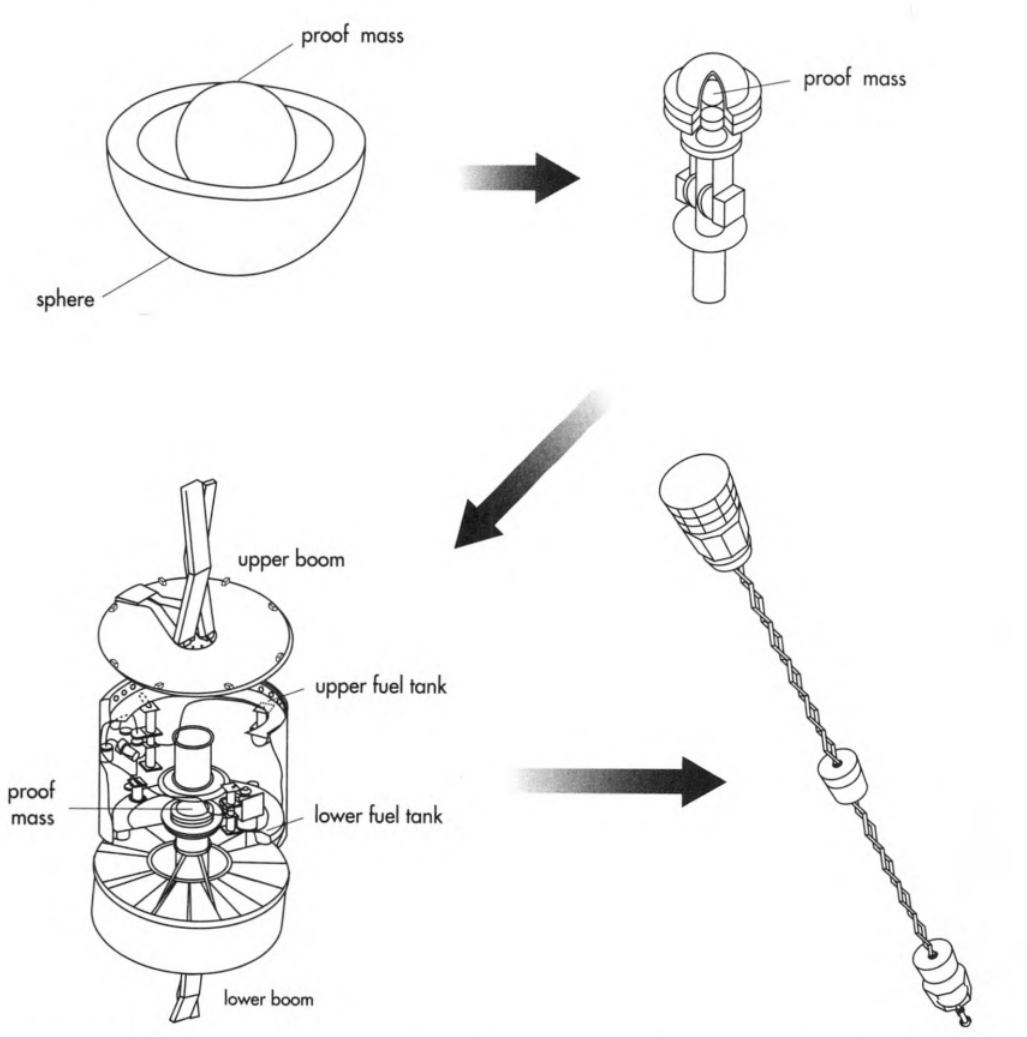

Figure 9.3.1: "Conscience-guided" satellite. A satellite in orbit around Earth is subject to small accelerations due to solar radiation pressure and residual atmospheric drag. Uncorrected, these accelerations are between 10^{-6} g and 10^{-9} g, where g is the acceleration of gravity at Earth's surface. The acceleration was reduced to 5×10^{-12} g for more than a year in orbit by use of a conscience or proof mass and the Disturbance Compensation System (DISCOS) mounted on a TRIAD U.S. Navy satellite. The conscience, a gold-platinum sphere 2.2 centimeters in diameter, floats freely inside a spherical housing. Any nongravitational force results in an incremental velocity change. The floating proof mass continues in its original state of motion in an ideal friction-free environment. Observing the proof mass through capacitor sensing devices, the satellite becomes aware that it is not keeping up with the motion demanded by the proof mass. An opposite vernier rocket fires long enough to bring the spaceship back into concord with its proof mass - its conscience. To reduce gravitational effects of the satellite itself on the proof mass, fuel for the vernier rockets is stored in donut-shaped tanks placed symmetrically above and below the proof mass; power supply and radio transmitter are each beld at the end of a boom 2.7 meters long on either side of the control unit. For an Earth-based microgravity environment, recall Figure 2-3. (Used with permission of AIAA. Journal of Spacecraft.)

FIGURE 9-2.

ISAAC NEWTON

Woolsthorpe, December 25, 1642—Kensington (London), March 20, 1727

Figure 9.3.2: Reprinted by permission of the publisher, Horizon Press, from Essays in Biography by John Maynard Keynes. Copyright 1951.

> *"The marble index of a mind forever*
>
> *Voyaging through strange seas of thought, alone."-Wordsworth*

> *ot know what I may appear to the world; but to myself I seem to have been only like a boy, playing on the sea-shore, and diverting myself, in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me." - Newton*

> *"Why do I call him a magician? Because he looked on the whole universe and all that is in it as a riddle, as a secret which could be read by applying thought to certain evidence, certain mystic clues which God had laid about the world to allow a sort of philosopher's treasure hunt to the esoteric brotherhood. He believed that these clues were to be found partly in the evidence of the heavens and in the constitution of elements (and that is what*

> *gives the false suggestion of his being an experimental natural philosopher), but also partly in certain papers and traditions handed down by the brethren in an unbroken chain back to the original cryptic revelation in Babylonia. He regarded the universe as a cryptogram set by the Almighty-just as he himself wrapt the discovery of the calculus in a cryptogram when he communicated with Leibnitz. By pure thought, by concentration of mind, the riddle, he believed, would be revealed to the initiate."-Keynes*

"Conscience-guided" satellite. What guides the conscience?

As satellite and proof mass come to empty space, they fly through it in perfect step, without use of rockets or sensing devices. What a remarkable harmony they present! The inner proof mass does not see outer space. It does not touch, feel, or see the ship that surrounds it on every side. Yet it faithfully tracks the ship's route through spacetime. Moreover, this tracking is as perfect when the proof mass is made of aluminum as when it is made of gold. How do proof masses - of whatever atomic constitution and whatever construction - know enough to follow a standard worldline? Where does mass get its moving orders?

Locally, answers Einstein. From a distance, answers Newton.

Einstein says that the proof mass gets its information in the simplest way possible. It responds to the structure of spacetime in its immediate vicinity. It moves on a straight line in the local free-float frame. No simpler motion and no straighter motion can be imagined.

Newton says that the inner proof mass gets its information about how to move from a distance, via a "force of gravity." Motion relative to what? Motion relative to an ideal, God-given, never-changing Euclidean reference frame that spans all of space and endures for all time. He tells us that the proof mass would have moved along an ideal straight line in this global frame had not Earth deflected it. How can this ideal line be seen? How sad! There is nothing, absolutely nothing, that ever moves along this ideal line. It is an entirely imaginary line. But it nevertheless has a simple status, Newton tells us, in this respect: Every satellite and every proof mass, going at whatever speed, is deflected away from this ideal line at the same acceleration (Figure 9.3.3).

Physics is simple only when analyzed locally.

Einstein says: Face it; there is no ideal background Euclidean reference frame that extends over all space. And why say there is, when even according to Newton no particle, not even a light ray, ever moves along a straight line in that ideal reference frame. Why say spacetime is Euclidean on a large scale when no evidence directly supports that hypothesis? To try to set up an all-encompassing Euclidean reference frame and attempt to refer motion to it is the wrong way to do physics. Don't try to describe motion relative to faraway objects. And locally the worldline that a satellite follows is already as straight as any worldline can be. Forget all this talk about "deflection" and "force of gravitation." I'm inside a spaceship. Or I'm floating outside and near it. Do I feel any "force of gravitation?" Not at all. Does the spaceship "feel" such a force? No. Then why talk about it? Recognize that the spaceship and I are traversing a region of spacetime free of all force. Acknowledge that the motion through that region is already ideally straight.

How can one display the straightness of the motion? Set up a local lattice of meter sticks and clocks, a local free-float (inertial) reference frame-also called a Lorentz reference frame (Chapter 2). How does one know the frame is free-float? Watch every particle, check every light ray, test that they all move in straight lines at uniform speed relative to this frame. And having thus verified that the frame is free-float, note that the proof mass too moves at a constant speed in a straight line-or remains at rest - relative to this local free-float frame. What could be simpler than the moving orders for mass: "Follow a straight line in the local free-float reference frame." Does a proof mass have to know the location of Earth and Moon and Sun before it knows how to move? Not at all! Surrounded on all sides by the black walls of a satellite, it has only to sense the local structure of spacetime-right where it is - in order to follow the correct track.

Physics is simple only when analyzed locally

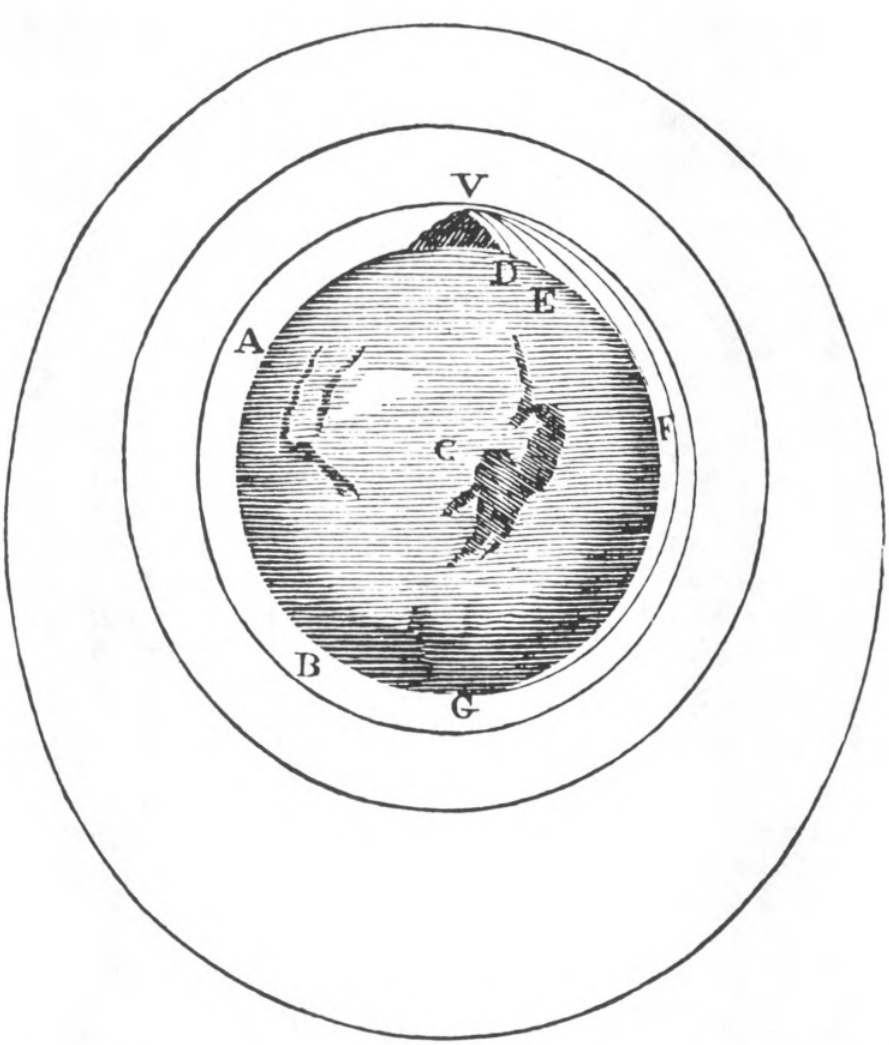

Figure 9.3.3: In Newtonian mechanics different particles going at different speeds are all deflected away from the ideal straight line with equal acceleration. In this respect there is no difference in principle between the fall of a projectile and the motion of a satellite. In this picture of Newton's published in 1686 , cannon of successively greater power mounted on a mountaintop fire out their balls horizontally. The more powerful cannon launches a satellite. The outer two curves show other possible satellite orbits. In brief, Newton bas one global reference frame, but within this reference frame no satellite is ever gravity-free, and no particle ever moves in a straight line at constant speed. Einstein, in contrast, makes use of many local regions in each of which the geometry is Lorentzian (as in special relativity); the laws of gravitation arise from the lack of ideality in the relation between one local region and the next (gravitation; spacetime curvature; general relativity).

Figure 9.3.1: Figure and data from Journal of Spacecraft, Volume 11 (September 1974), pages 637-6 4 4 , published by the American Institure of Aeronautics and Astronautics. Data also from D. B. De Bra, APL Technical Digest, Volume 12: pages 14-26.

Figure 9.3.2 from Philosophiae Naturalis Principia Mathematica (Joseph Streater, London, July 5, 1686); Morre translation into English revised and edited by Florian Cajori and published in two paperback volumes (University of California Press, Berkeley, 1962). This is also the source of rhe quote in Section 9.6: "Absolute space, in its own namre, without relation to anything external, remains always similar and immobile."