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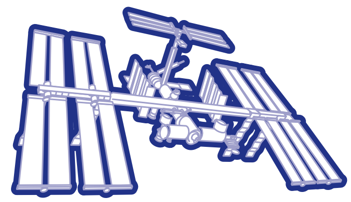
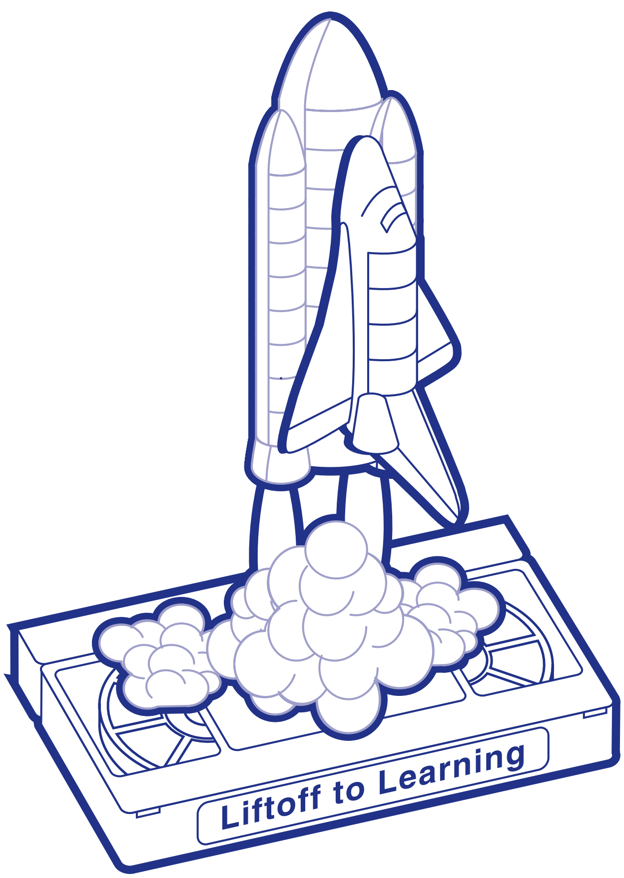


Tethered Satellites

Parts 1 & 2

A Videotape for Physical Science



Video Resource Guide

EV-1997-07-011-HQ

Video Synopsis

Title: Tethered Satellites
Part 1 - Tethered Satellite Forces and Motion
Part 2 - Electrical Circuits in Space: The Electrodynamics of the Tethered Satellite

Length: Part 1 - 21 minutes, 11 seconds
Part 2 - 18 minutes, 50 seconds

Subjects: Part 1 - Force, motion, and gravity
Part 2 - Electricity and magnetism

Description:

Part 1 describes the tethered satellite concept and shows how the satellite is deployed and extended in space. The mathematics describing the forces acting on the tethered satellite/Space Shuttle orbiter system is presented.

Part 2 demonstrates how the tethered satellite and the Space Shuttle orbiter interact with Earth's magnetic field to produce an electric current. Future applications of the tethered satellite/Space Shuttle orbiter system as a motor are described.

Science Standards:

Physical Science
- Position and motion of objects
- Properties of objects and materials

Unifying Concepts and Processes
- Change, constancy, and measurement
- Evidence, models, and exploration

Science Process Skills:

Observing
Measuring
Predicting
Making Models
Defining Operationally
Investigating

Mathematics Standards:

Problem Solving
Reasoning
Computation and Estimation

Background

In 1992 and again in 1996, NASA and the Italian Space Agency (ASI) tested a concept for a tethered satellite. Deployed from the payload bays of the Space Shuttles *Atlantis* (STS-46) and *Columbia* (STS-75), the spherical 1.6-meter-diameter satellite was reeled out into space. Its tether, a 21-kilometer-long leash, consisted of a core of Nomex® wrapped with copper wire and covered with a protective sheath of Kevlar® and additional Nomex®. For deployment, a 12-meter boom elevated the satellite out of the payload bay so the satellite would not hit the orbiter. Small thrusters on the satellite gave it its initial push into space. Once moving, forces on the orbiter-tethered satellite system kept the satellite and orbiter moving apart from each other.

Tethered Satellite Mission Objectives

The primary scientific and engineering objectives of tethered satellite missions were to deploy, stabilize, and retrieve a tethered satellite in space and operate it as an electrically conducting system within Earth's magnetic field. Manipulating a satellite on a tether from the orbiter turned out to be a unique engineering challenge. Because gravity, centrifugal acceleration, and atmospheric drag vary with altitude, each of the two bodies in a tethered system, one orbiting above the other, is subject to different magnitudes of influence.

On both missions significant technical problems occurred. On STS-46, the tethered satellite jammed twice on the reel while the satellite was 179 and later 256 meters away from the orbiter. The satellite could not be deployed any further. On STS-75, the satellite was extended 19.7 kilometers when the tether broke near the boom. The satellite and tether drifted away safely from the orbiter and were not retrievable. Up to the time of the severing of the tether, the orbiter-tethered satellite system had been generating 3,500 volts and up to 0.5 amps of current.

Later investigation of the problems that occurred on the two missions determined that the tether on the first flight was snagged by the mechanism that unreeled it from the orbiter. The break of the tether on the second mission occurred because of either a flaw in the insulation or the penetration of a foreign object into the insulation causing an electrical arc from the tether to a nearby ground. The arcing severed the tether.

In spite of these problems, each major objective was met. The flights demonstrated that the tethered satellite would deploy and the forces acting on the satellite and the orbiter worked to keep the satellite extended from the orbiter without additional thruster firing. Both missions also demonstrated that tethered satellites will generate an electric current as they pass through Earth's magnetic field.

Part 1 of this video concentrates on the forces and motions acting on the tethered satellite and Space Shuttle orbiter. Orbital scenes were taken on the STS-46 mission which launched on July 31, 1992. Part 2 of this video concentrates on the electrodynamics of the tether in space.

Mathematical Equations Illustrated in the Video

To explain the dynamics of the tethered satellite system, the following equations appear in Part 1:

Newton's Second Law of Motion

$$F = ma$$

Force equals mass times acceleration.

Universal Law of Gravitation

$$F \propto \frac{m_1 m_2}{r^2}$$

For two masses, the attractive force of gravity between them is proportional to the product of their masses and inversely proportional to the square of the distance between their centers of mass.

During the video, students are challenged to verify the relationship between the distance the tethered satellite moves during deployment and the distance the Space Shuttle moves. The following data were provided:

Mass of the Space Shuttle - 100,000 kg
Mass of the tethered satellite - 500 kg
Distance the Space Shuttle moves - 100 m
Distance the tethered satellite moves - 20,000 m

$$m_{ts} \times d_{ts} = m_{ss} \times d_{ss}$$

$$500\text{kg} \times 20{,}000\text{ m} = 100{,}000\text{kg} \times 1{,}000\text{m}$$

To explain the electrical nature of the tethered satellite system, the following equations appear in Part 2:

Ohm's Law

$$i = \frac{v}{r}$$

This law states that the amount of current (i) in an electrical circuit is directly proportional to the voltage (v) of the circuit and inversely proportional to the resistance (r) of the circuit. Two variations of the equation above are used in the video. The equations and the values used in the video are given below.

$$r = \frac{v}{i} = \frac{4{,}800}{0.5} = 9{,}600 \text{ ohms } (\Omega)$$

$$i = \frac{v}{r} = \frac{1{,}000}{500} = 2 \text{ amps (A)}$$

Lorenz Force

An electron passing through a magnetic field experiences a force that is perpendicular to both the direction of motion and Earth's magnetic field.

BxVxL = voltage

Earth's magnetic field x velocity of tether x tether length = voltage

$3\text{x}10^{-5}$ tesla x 8,000 meters per second x 20,000 meters = 4,800 volts

Terms

Amperage - This is the measure of the amount of electrical current flowing through a circuit. The unit of measurement is the ampere (one coulomb of charge per second).

Angular momentum - The product of an object's rotational velocity and its rotational inertia about an axis.

Center of Mass - A single point about which the mass of an object is considered to be concentrated.

Circuit - A complete pathway along which an electrical current can flow.

Conductor - A material through which an electrical current can flow.

Conservation of Angular Momentum - As long as no external torques are exerted, the angular momentum of an object remains constant.

Conservation of Energy - Energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes.

Coriolis Effect - The deflection of a moving object into a curved path due to Earth's rotation.

Current - A flow of an electric charge between two points in which there is a difference in potential.

Equilibrium - The state of an object when not acted upon by a net force or net torque.

Force - a push or pull that causes an object to accelerate.

Gravity - The attraction of objects to one another due to their mass.

Gravity Gradient Force - Differences in the force of gravity felt in various parts of a system due to varying distances from the center of Earth.

Inertia - A property of matter causing it to resist changes in motion.

Inverse Square Force (law) - A law relating the intensity of an effect to the inverse square of the distance from the cause.

Ion - An atom that has an electrical charge due to the loss or gain of electrons.

Ionosphere - The upper region of Earth's atmosphere extending from about 85 to 1,000 kilometers. This region is also called the thermosphere.

Lorenz Force - Electrons moving through a magnetic field experience a force that is perpendicular to both the direction of motion and the magnetic force lines.

Magnetic Field - The force field that surrounds every magnet and electrical current-carrying conductor.

Newton - A unit of force: 1 Newton accelerates a mass of 1 kilogram 1 meter per second.

Ohm - The unit of measurement for electrical resistance in a circuit. The resistance of a device that draws a current of one ampere when one volt is impressed across the circuit.

Potential - The electric potential energy at a point within an electrical circuit.

Rendezvous - In spaceflight, the close approach of two spacecraft traveling in the same orbit.

Resistance - A property of a conductor that causes it to resist the flow of electricity. The unit of measurement is the ohm.

Resonance - Phenomenon where energy is transferred to an object at its natural vibration frequency by a second object or wave vibrating at that same frequency.

Restoring Force - A force that returns equilibrium to a system.

Tesla - The unit of measure for a magnetic field (Webber/m^2).

Tethered Satellite - A satellite attached to another space vehicle by means of some sort of cord.

Torque - A product of force and lever-arm distance, which tends to produce rotation in an object.

Voltage - The measure of the electric potential difference in a circuit. The electric potential at which one coulomb of charge would have one joule of potential energy.

Classroom Activities

The following hands-on activities demonstrate some of the concepts presented in these two programs.

Conserving Angular Momentum

Materials
Rotating stool or rotating platform
Two exercise hand weights (1 to 2 kg each)

Background
The Space Shuttle orbiter/tethered satellite system operates under the law of the conservation of angular momentum as it orbits Earth. Angular momentum is a product of the rotational inertia of an object and its rotational speed. The system can be compared to a spinning ice skater. When the skater tucks his or her arms in tightly, rotational speed increases while rotational inertia decreases. Discounting frictional effects, the skater's angular momentum is conserved. When the skater's arms are extended, rotational speed decreases while rotational inertia increases. Again, angular momentum is conserved. Like a skater extending arms, when the tethered satellite is extended above the orbiter, its distribution of mass is changed. The rotational inertia of the system is conserved by decreasing its rotational speed while increasing its rotational inertia. The reduction of rotation speed actually lowers the orbiter in its orbit. However, when the tethered satellite is retrieved, rotational speed increases as rotational inertia decreases. Because angular momentum is again conserved, the orbiter actually raises its altitude. The following activity permits students to experience the conservation of angular momentum.

Procedure
1. Place the rotating stool or platform in the middle of a clear area at least 2-3 m across.
2. Have a student sit on the stool or stand on the platform.
3. Give the student the two hand weights and ask the student to extend his or her arms.
4. Gently start the student spinning while standing nearby to help the student maintain balance.
5. On command, the student should move the weights to his or her chest. What happens to the student's rotation rate? Is the student gaining momentum?
6. Once the student becomes accustomed to balancing on the stool or platform, the rotation rate can be increased slightly to dramatize the effect.

Discussion and Extensions
1. Besides figure skaters, can you think of other examples of conservation of angular momentum?
2. How could a tethered satellite be used to alter spacecraft orbits without the expenditure of rocket propellant?
3. Additional information on the conservation of angular momentum can be found in any physics textbook.

Seesaw

Materials

Moment of Force Apparatus or the items listed below:
Meter stick
10 large metal washers
Small triangular block or other object to serve as a fulcrum

Background

When a Space Shuttle orbiter deploys a tethered satellite, the center of mass of the two bodies remains in a constant orbit. What changes is the respective distance of the two bodies from that center of mass. Because it contains far less mass than the orbiter, the tethered satellite travels a great distance in one direction while the orbiter moves a short distance the opposite way. The orbiter has a mass of about 100,000 kg and the tethered satellite has a mass of 500 kilograms. When the tethered satellite is deployed to a distance of 20 kilometers, the orbiter moves about 100 meters in the opposite direction. The center of mass of these two bodies remains constant.

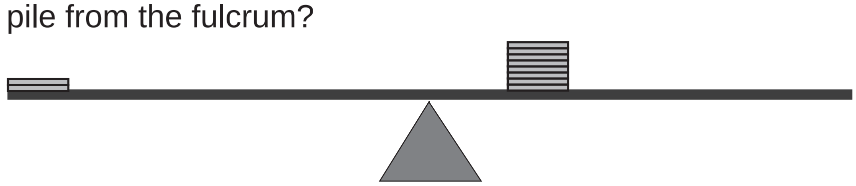
Procedure

(Follow the instructions that come with the Moment of Force Apparatus or use these instructions with the alternative apparatus)

1. Place the meter stick on the fulcrum so that it balances.
2. Divide the washers into two equal piles and place them on opposite sides of the fulcrum. Adjust the positions of the piles to bring the stick into balance by moving them closer or farther from the fulcrum. How far is each pile from the fulcrum?
3. Divide the washers into two piles of two and eight washers respectively. Place them on the meter stick and adjust their positions until the stick is in balance. How far is each pile from the fulcrum?
4. Is there a mathematical relationship between the masses of the two piles and their distances from the fulcrum? How does this activity relate to the deployment of tethered satellites?

Discussion and Extensions

1. How far would a Space Shuttle orbiter move if a tethered satellite with a mass of 2000 kilograms were deployed to a distance of 10 kilometers?



Tether Oscillations

Materials
Solid ball
Elastic cord

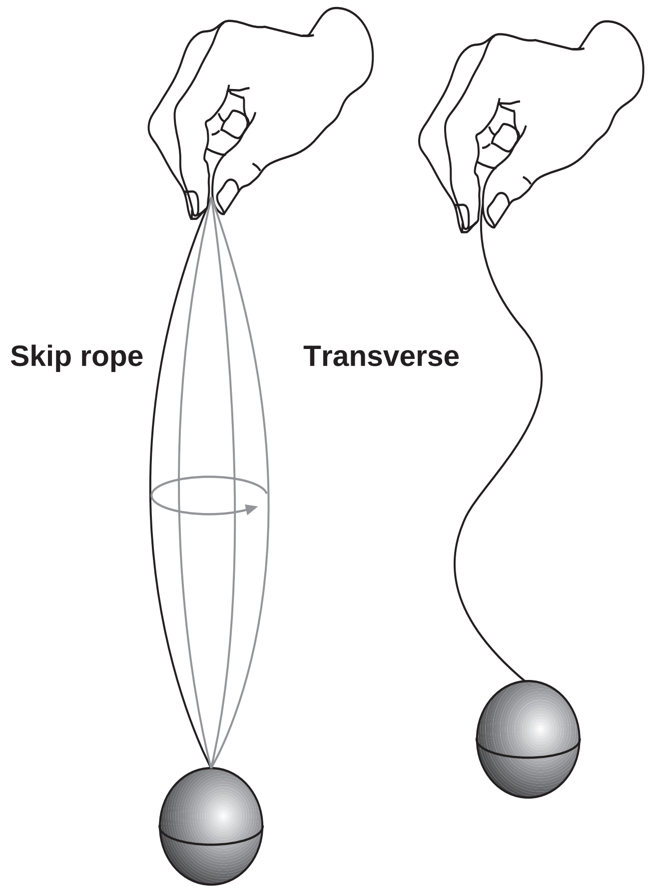
Background
The oscillations that can occur with a tethered satellite system can be reproduced with a ball attached to an elastic cord. The tether may compress and stretch, causing the satellite to bounce up and down (longitudinal oscillation). The satellite and tether may move in a circular (skip rope) fashion. The satellite can remain fairly still but the tether can oscillate (transverse).

Each type of oscillation occurs with a particular frequency, which in turn depends upon the length and tension of the tether. When frequencies are different, the motions do not interact. However, at some tether lengths, the frequencies of two or more oscillations can become very close. Energy can be transferred from one type of oscillation to another in a phenomenon known as resonance.

Many different factors, such as control motions of the Space Shuttle, can trigger oscillations. One of the tethered satellite experiments is to use the interaction of the tether with Earth's magnetic field to generate an electric current. When a current is produced, another magnetic field is created. The two fields may interact, (if the current is pulsed at the natural frequency) causing the tether to skip rope.

Procedure
1. Attach an elastic cord to a solid ball.
2. Suspend the ball by holding the opposite end of the elastic. Create the following oscillations:
   - Longitudinal (bounce ball up and down by raising and lowering your hand)
   - Transverse (with the ball hanging still, move your hand from side to side)
   - Skip rope (with the ball hanging still, move your hand in a circle)

Discussion and Extensions
1. Why is it important for scientists to study possible oscillations of tethered satellite systems?
2. Could there be other kinds of oscillations that might affect the tethered satellite?
3. How can oscillations affect structures on Earth?



Magnetic Fields

Materials

Bar magnet
Iron filings
Sheet of white paper or overhead projector tranparency paper
Plastic sandwich bag
Overhead projector (optional)

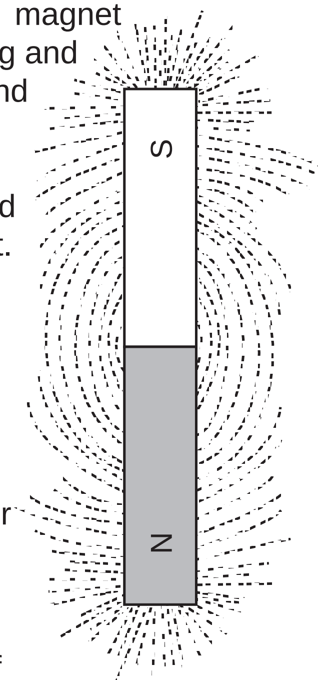
Background

The Space Shuttle orbiter/tethered satellite system makes use of Earth's magnetic field and its electrically charged ionosphere to produce a current through the tether. The way the current is produced will be discussed in the next activity.

All magnetic objects produce invisible lines of force that extend between the poles of the object. This phenomenon is visualized with iron filings sprinkled around a bar magnet. In very simple terms, Earth can be thought of as a dipole (2 pole) magnet. Magnetic force lines radiate between Earth's north and south magnetic poles. Electrically charged particles become trapped on those field lines just as iron filings become trapped on the force lines of the bar magnet. The particles are able to move along the force lines, and when they contact thin gases near Earth's polar regions, trigger auroral displays. Unlike the symmetrical field of the bar magnet, Earth's magnetic field is asymmetrical. On the sunlit side of Earth, the pressure of the solar wind (streams of electrically charged particles ejected from the Sun) compresses the magnetic force lines, while on the far side, the lines are stretched out.

Procedure

1. Lay a bar magnet on a table top and cover it with a sheet of white paper.
2. Carefully sprinkle iron filings on the paper to delineate the magnetic force lines.
3. Make a sketch of the patterns of the magnetic filings.
4. Optional. Lay the magnet on the stage of an overhead projector and cover the magnet with a sheet of transparency paper. Sprinkle the filings over the magnet and project the patterns on the screen.
5. Return the iron filings to the storage container by shaping the paper into a funnel. Place a bar magnet inside a sandwich bag and sweep the area around the magnet for filings that escaped. Turn the bag inside out and pull away the magnet.



Discussion and Extensions

1. What creates the magnetic field of Earth?
2. Do other bodies in our solar system have magnetic fields?
3. Sprinkle iron filings around other kinds of magnets, such as ring magnets, to observe their magnetic fields.
4. Make a permanent magnetic field indicator by placing iron filings between two tranparency sheets or sheets of scrap laminating film and hot gluing the edges of the sheets together.

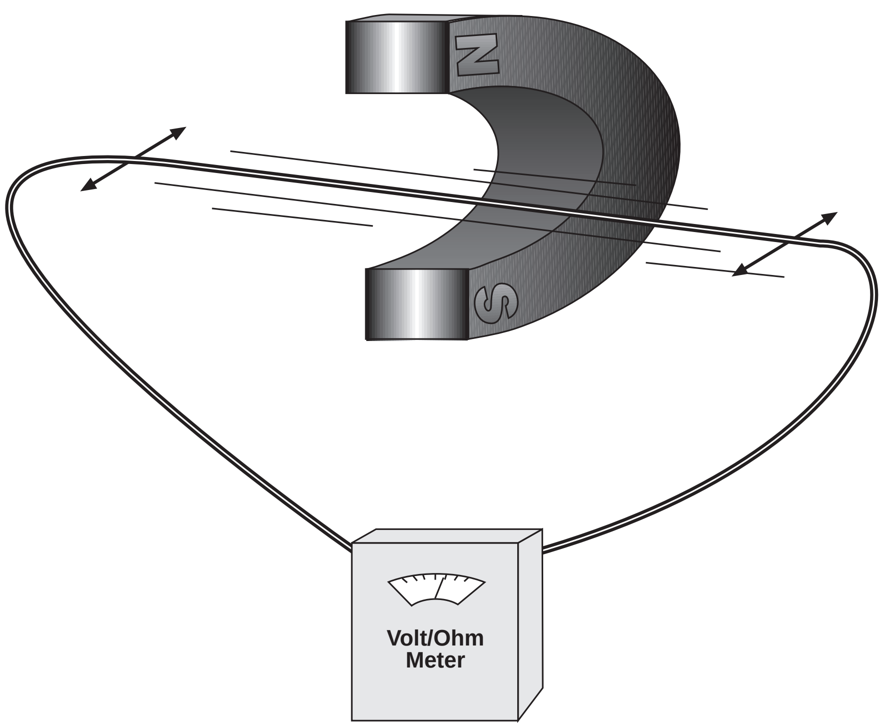
Generating Currents

Materials
Powerful magnet
Copper wire
Volt/ohm meter

Background
As the Space Shuttle orbiter/tethered satellite system orbits Earth, the tether rapidly cuts across Earth's magnetic force lines. The interaction creates an electric current that travels through the conductor of the tether. The effect is analogous to the way power is generated by an automobile alternator. Free electrons in the thin ionosphere where the Space Shuttle operates are attracted to the satellite. The electrons travel along the tether to the orbiter. However, in order for the current (a flow of charged particles) to be produced, a complete circuit must be formed. This is accomplished by using an electron generator on the orbiter to return charged particles back into the ionosphere.

Procedure
1. Connect the wire to the terminals of the volt/ohm meter. Set the meter to a low voltage range.
2. Quickly move the wire through the magnet's magnetic field. Observe the meter's display to see if a current is produced.
3. Move the wire at different speeds through the magnetic field and observe the amount of voltage produced.

Discussion and Extensions
1. What is the relationship between the speed of the moving wire and the voltage produced?
2. How do traditional electric generators work?



References

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STS-46 and 75 Crew Biographies

Commander STS-46: Loren J. Shriver (Col., USAF). Loren Shriver was born in Jefferson, Iowa, but considers Paton, Iowa, his hometown. He earned a bachelor of science degree in aeronautical engineering from the United States Air Force Academy and a master of science degree in astronautical engineering from Purdue University. After graduation from the Air Force Academy, Shriver served as a T-38 academic instructor pilot and completed F-4 combat crew training. Following an overseas tour in Thailand, he graduated from the USAF Test Pilot School at Edwards Air Force Base, California. He participated in the Air Force development tests and evaluations of the F-15 fighter and T-38 lead-in fighter aircraft. Shriver, who has logged more than 6,000 hours in jet aircraft, became an astronaut in 1979 and has flown in space as the pilot on the STS-51C mission and as commander on the STS-31, and STS-46 missions.

Commander STS-75: Pilot STS-46
Andrew M. Allen (Lt. Colonel, USMC)
Andrew Allen was born in Philadelphia, Pennsylvania. He received a BS degree in mechanical engineering from Villanova University where he was a member of the Navy ROTC and where he received his commission from the United States Marine Corps. A graduate of the United States Naval Test Pilot School, Allen was a test pilot and flew such high performance jet aircraft as the F-4 Phantom and the F/A-18 Hornet. He is also a graduate of the Marine Weapons and Tactics Instructor Course and the Naval Fighter Weapons School (Topgun). As a military pilot, Allen logged over 5,000 flight hours in more than 30 different aircraft. Andrew Allen is a veteran of three spaceflights. He served as the pilot on the first two flights and on his third flight (STS-75), was the commander. Allen was also a member of the crew that first deployed the tethered satellite and appears in both videos.

Mission Specialist STS-46 and STS-75: Claude Nicollier (ESA). Claude Nicollier was born in Vevey, Switzerland. He holds a bachelor of science degree in physics from the University of Lausanne and a master of science degree in astrophysics from the University of Geneva. Nicollier worked as a graduate scientist with the Institute of Astronomy at Lausanne University and at the Geneva Observatory. His research in the field of stellar photometry included several stays at mountaintop observatories in Switzerland and Chile. In 1978, he was selected by the European Space Agency (ESA) as a payload specialist to train for the Spacelab-1 mission.

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Through an agreement between NASA and ESA he became a mission specialist astronaut in 1980. He holds a commission as captain in the Swiss Air Force and has logged 5,400 hours flying time, including 3,800 hours in jet aircraft. He also flew DC-9s for three years (1974-1976), and is a 1988 graduate of the Empire Test Pilot's School. Nicollier has flown in space on the STS-46, 61, and 75 missions.

Mission Specialist STS-46: Marsha S. Ivins. Marsha Ivins was born in Baltimore, Maryland. She earned a bachelor of science degree in aerospace engineering from the University of Colorado. She worked as an engineer in Man Machine Engineering, as a flight simulation engineer on the Shuttle Training Aircraft, and as copilot of the NASA administrative aircraft at the Johnson Space Center. Ivins was selected as an astronaut in 1984. Ivins, who has logged more than 4,700 hours in civilian and NASA aircraft, flew in space as a mission specialist on the STS-32, STS-46, STS-62, and STS-81 missions.

Mission Specialist STS-46 and STS-75: Jeffrey A. Hoffman, Ph.D. Jeffrey Hoffman was born in Brooklyn, New York, but considers Scarsdale, New York, to be his hometown. He earned a bachelor of arts degree in astronomy from Amherst College, a master of science degree in materials science from Rice University, and a doctor of philosophy degree in astrophysics from Harvard University. Dr. Hoffman has authored more than 25 professional journal articles during three years of post doctoral work at Leicester University in England, and three years at the Center for Space Research at the Massachusetts Institute of Technology in the field of x-ray astronomy. He became an astronaut in 1979 and has flown in space as a mission specialist on the STS-51D, STS-35, and STS-75, the payload commander on the STS-46 mission, and as an EVA crew member on STS-61 mission. Hoffman has conducted four space walks (three for servicing the Hubble Space Telescope).

Mission Specialist STS-46: Payload Commander STS-75: Franklin R. Chang-Diaz, Ph.D. Franklin Chang-Diaz was born in San Jose, Costa Rica. He earned a bachelor of science degree in mechanical engineering from the University of Connecticut and a doctorate in applied plasma physics from the Massachusetts Institute of Technology (MIT). During graduate school at MIT, he worked in the United States' controlled fusion program. He has logged over 1,500 hours of flight time. Dr. Chang-Diaz was named an astronaut in 1981. After being selected as an astronaut, he was appointed Visiting Scientist with the MIT Plasma Fusion Center where he led the Plasma Propulsion Group to develop plasma propulsion technology for future human missions to Mars. In 1994, he was appointed Director of the Advanced Space Propulsion Laboratory at the Johnson Space Center where he continues his research on plasma rockets. Dr. Chang-Diaz is an Adjunct Professor of Physics at the University of Houston. He has flown in space as a mission specialist on the STS-61C, STS-34, and STS-46 missions and was the payload commander on STS-60 and STS-75.

Payload Specialist STS-46 (ASI): Franco Malerba, Ph.D.
Franco Malerba was born in Genova, Italy. He received two doctorate degrees from the University of Genova, one in electronics engineering and telecommunications and the other in physics. In 1977, he was chosen by the European Space Agency as a payload specialist candidate for the first mission of Spacelab and worked at the ESA-ESTEC technical center in Noordwijk, The Netherlands, on the development of the space plasma physics experiment "PICPAB" which flew aboard the first Spacelab (STS-9) mission. Malerba also has done extensive

work in computer networks engineering and telecommunications technology and has served as a reserve officer in the Italian Navy. He flew in space as a payload specialist on the STS-46 mission. Malerba is now working with the Italian Space Agency's manned spaceflight program.

Pilot STS-75: Scott J. Horowitz (LTC, USAF, Ph.D.)

Scott Horowitz was born in Philadelphia, PA but considers Thousand Oaks, CA his home. He earned a bachelor of science degree in engineering from California State University at Northridge, a master of science degree in aerospace engineering, and a doctorate in aerospace engineering from Georgia Institute of Technology. Horowitz worked as an associate scientist for Lockheed-Georgia Company. He became a T-38 instructor pilot and an operational F-15 Eagle Fighter Pilot for the US Air Force. He later graduated from the USAF Test Pilot School. Horowitz also taught aeronautic courses as an adjunct professor at Embry Riddle University and as a professor at California State University at Fresno. In 1992, Horowitz was selected as a pilot astronaut. This was his first flight.

Mission Specialist STS-75: Maurizio Cheli (ESA)

Maurizio Cheli was born in Modena, Italy. He graduated from the Italian Air Force Academy, from the Italian Air Force War College, and from the Empire Test Pilot School. He received a master of science degree in aerospace engineering from the University of Houston. Cheli has logged more than 3,000 flying hours in 50 different fixed wing aircraft and helicopters. In 1992, he was selected by the European Space Agency as a member of the second group of European Astronauts. This was his first spaceflight.

Payload Specialist STS-75: Umberto Guidoni (ASI)

Umberto Guidoni was born in Rome and educated at the University of Rome where he received a bachelor of science degree in physics and a doctorate in astrophysics. Following graduation, Dr. Guidoni conducted research work as a National Committee for Nuclear Energy (CNEN) postdoctoral fellow and a guest scientist in the European Nuclear Energy Agency's (EURATOM) controlled fusion program. He also worked at the Space Physics Institute as a project scientist in charge of the development of a plasma experiment (RETE) that is one of the three science payloads mounted on the tethered satellite. A member of the Italian Space Society and author of professional journal articles, Guidoni was selected by the Italian Space Agency, ASI, as one of two Italian scientists to be trained as payload specialists for the first Space Shuttle tethered satellite mission. He was later assigned to the Astronaut Office at the Johnson Space Center for specialized space flight training. STS-75, was Guidoni's first Space Shuttle mission.

NASA Liftoff to Learning

Tethered Satellite Parts I & II

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Video Resource Guide

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