Astrodynamics

ASD6: Spacecraft Subsystems

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In this lecture, we provide a bird's-eye view of the various subsystems that constitute a satellite mission: launch, orbital, attitude, power, and RF/communication systems. We will delve into more detail (particularly into the RF/communication systems) later in the course, but this lecture will demonstrate the interconnectedness of the various spacecraft subsystems and how changing one influences the other.

Launch Systems

- Rockets required for Launch
  - Most earth-orbit satellites launched with rotation of the earth
  - Equator works best
  - Opposite orbit is called *retrograde*
- Rockets are the only known way to escape earth's gravity
  - Rockets are bombs with holes in them
  - Require fuel

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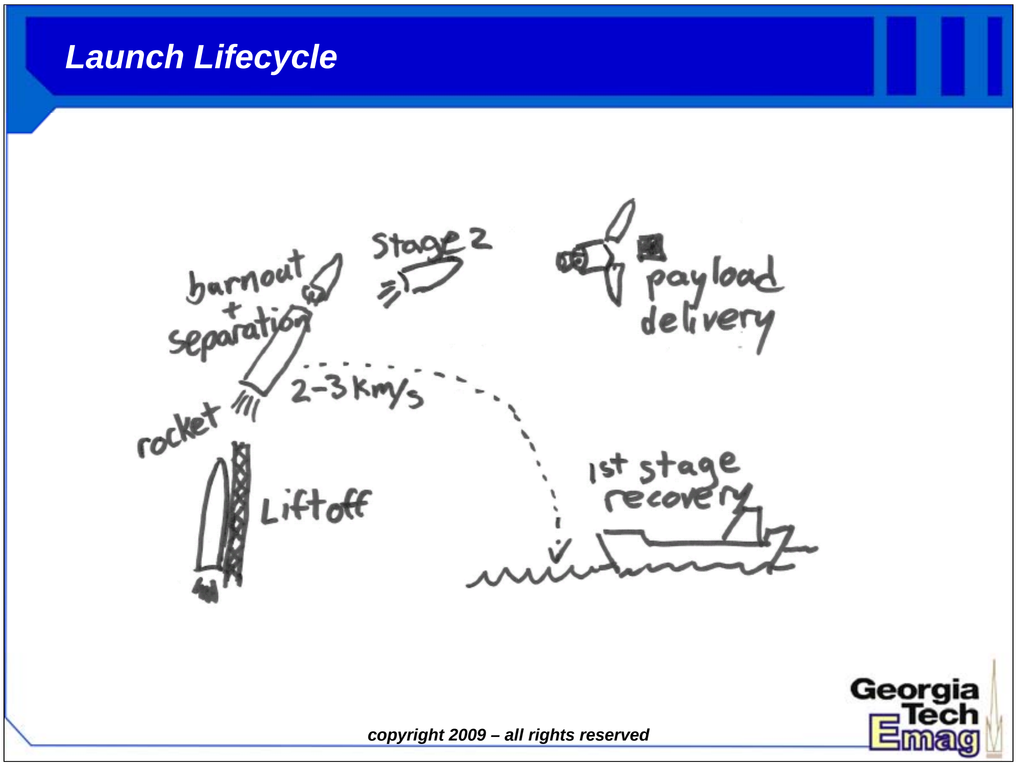
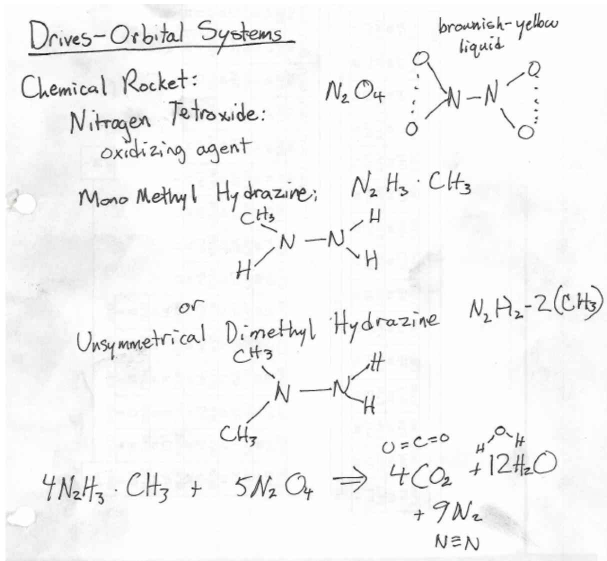
The first thing we must do is launch our satellite, which requires a rocket. Earth orbit satellites are typically launched in a direction coinciding with the rotation of the earth. In rare circumstances, a retrograde orbit is used, but requires a lot more energy for launch since the ground speed and direction of earth-based objects (due to rotation) provides a non-trivial boost for satellite launches. In fact, it is more beneficial to launch a satellite from the equator since an object's ground speed is maximized here. There is a company named "Sea Launch", in fact, that will put a rocket onto a floating launch pad (old oil rig platform), tug it down to the equator, and launch with minimal fuel. This explains why places like Florida are preferred launch sites for US spacecraft.



Rockets tend to come in two different flavors: solid fuel and liquid fuel. For the first couple decades of the space program, the general rule of thumb at NASA was that solid fuel was for payload rockets while liquid fuel was for manned missions. The reason: liquid fuel rockets can be turned-off, while solid fuel rockets must completely burn-out once started – thus, liquid fuel rockets can be considered slightly safer for manned missions. Note, however, that the space shuttle used solid rocket boosters and the new manned orbiter planned by NASA will also employ solid rocket fuel, as solid fuel rockets have become more reliable over time.

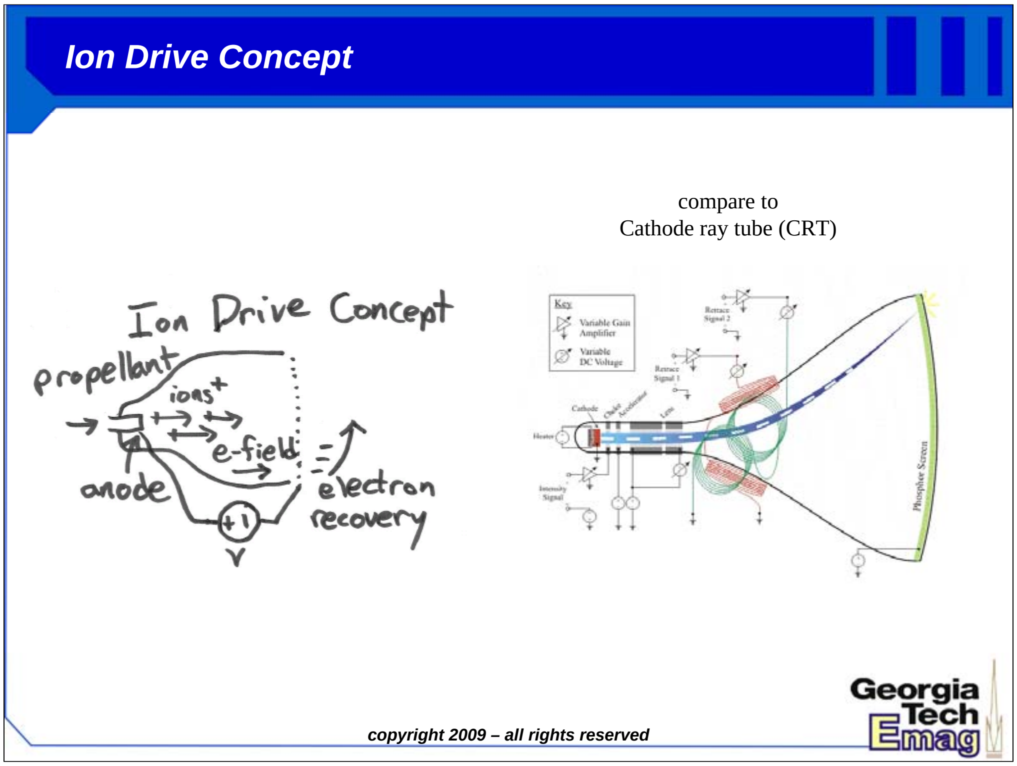
For higher orbits, it is often necessary to perform a multi-stage launch where stage 1 places the rocket in a low-earth orbit and a second stage propels the spacecraft into a higher-energy orbit … or beyond. The husk of the first-stage rocket, which still has salvage value, may be recovered over the ocean after it drops back to earth.

Chemistry of Thrust



Rockets are always dangerous because they are essentially bombs with holes in them. Rocket fuel typically consists of a base combustible fuel and an oxidizing agent. Both tend to have lots of nitrogen components, since nitrogen in chemical reactions generates quick-forming, highly energetic diatomic gas molecules. These are really the desirable attributes of rocket (and other explosive) reactions: energetic, quick forming, and high-volume expanding. Thus, any liquid or solid compound that forms a lot of hot gas particles under combustion make for an excellent rocket fuel.

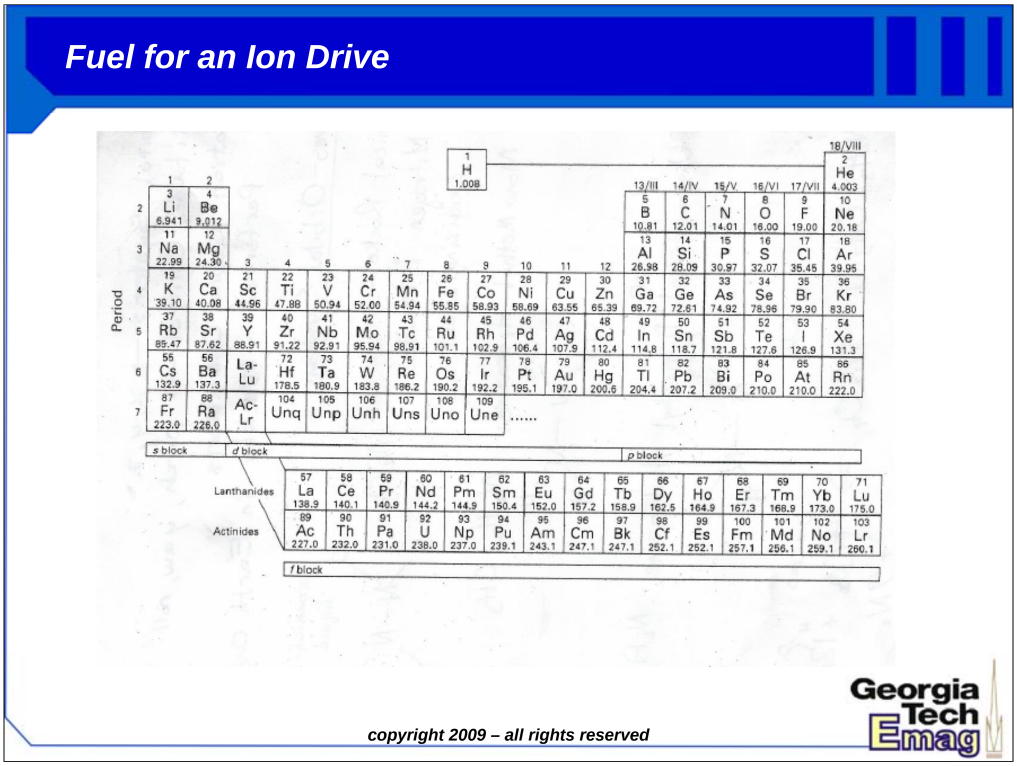
Above is the chemical formula for some common rocket-fuel components. Nitrogen tetroxide is used as an oxidizing agent (solid compound with nitrogen and lots of oxygen). Hydrazine compounds, like monomethyl hydrazine or dimethyl hydrazine, is often used as a propellant. The chemical formula for the combustion of these compounds demonstrates their efficacy as a propellant. The solid compounds all produce energetic gasses which rapidly expand in volume, out the rocket nozzle. Conservation of momentum kicks in, and the rapid gas discharge imparts equal and opposite momentum to the rocket and its payload.



Once in space, other forms of propulsion become feasible. For example, an ion drive may be used to propel spacecraft to higher earth orbits or onto deeper space missions. Such a drive works by ionizing gasses and electrically accelerating them out the back side of the drive. Again, conservation of momentum leads to thrust in the forward direction.

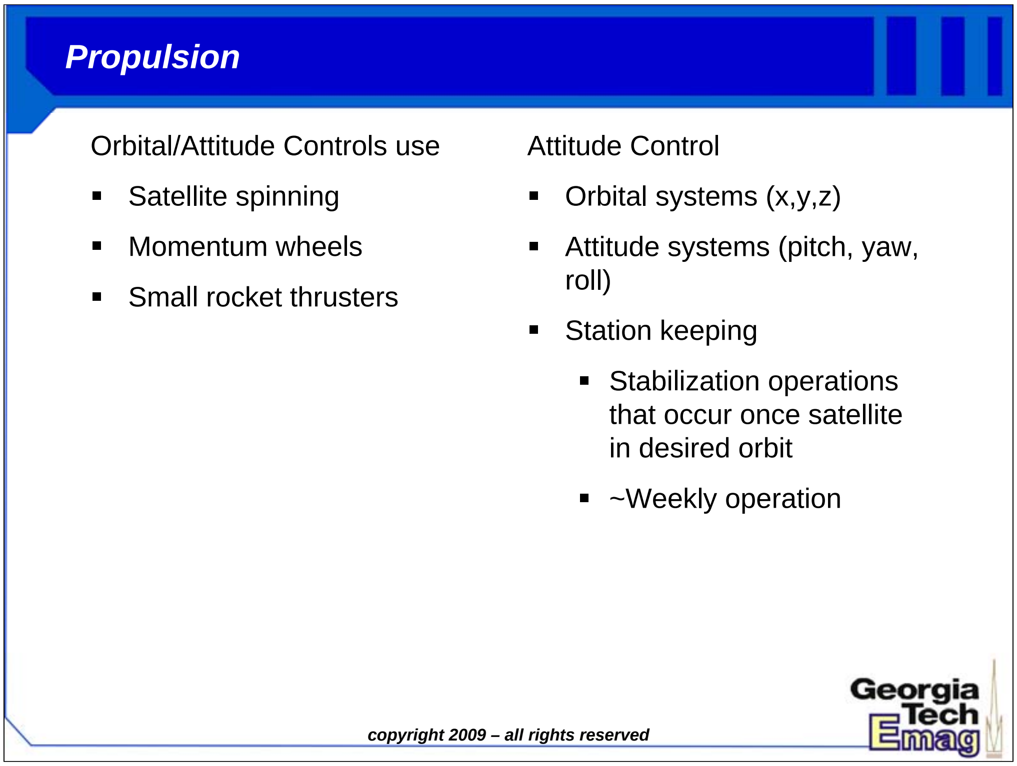
This thrust could never be use to escape earth's atmosphere … a typical thrust for these drives is 1/50th of a pound! However, the extraordinary attribute of these drives are there high thrust-to-weight ratio. By using an electrical drive (the electronic fields can be made by stepping up DC voltage from a solar cell) and shooting out a trickle of high-velocity ions, the total amount of momentum discharged by an ion engine over time is very high.

In space 1/50th of a pound of thrust is significant as, over time, this can still build up to extraordinary cumulative accelerations, largely because space is a drag-free environment.



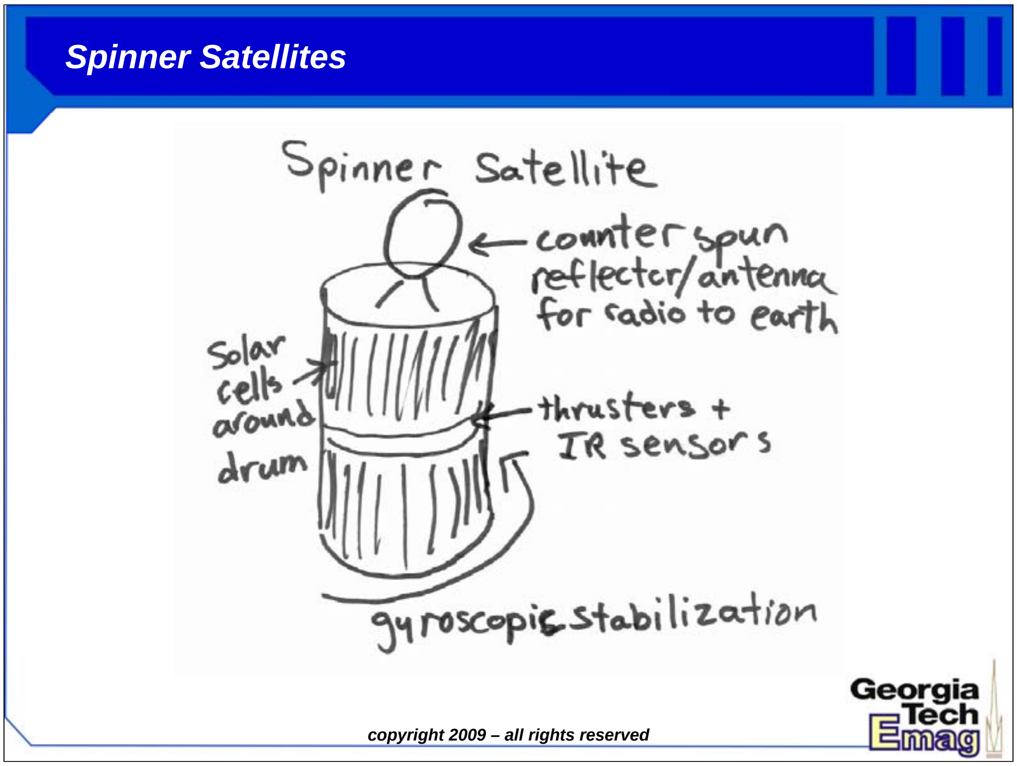
The fuel for an ion drive is typically a high-atomic weight gas. To figure out which gas works the best, let's look at the periodic table. Most of the gases in the table are on the far-right column – in fact, these are the noble gasses since they do not typically form compounds with other atoms or even diatomic molecules with one another. Under pressure and low temperature, these gasses can be compressed into a liquid and stored for fuel. When ready to use some in the ion drive, the individual atoms are stripped of their electrons through a variety of means (heat, RF energy, etc.) and the positive nucleus is accelerated to high speed out the back side of the drive. Their much lower-mass electrons are injected back into this exhaust plasma (so the spacecraft does not become increasingly negative and re-attract its positively-charged exhaust!)

The heavier the nucleus, the greater potential for imparting opposite momentum to the spacecraft. Looking down the noble gas column, we find that Xenon makes the best fuel (Radon is heavier, but has some other obvious drawbacks).



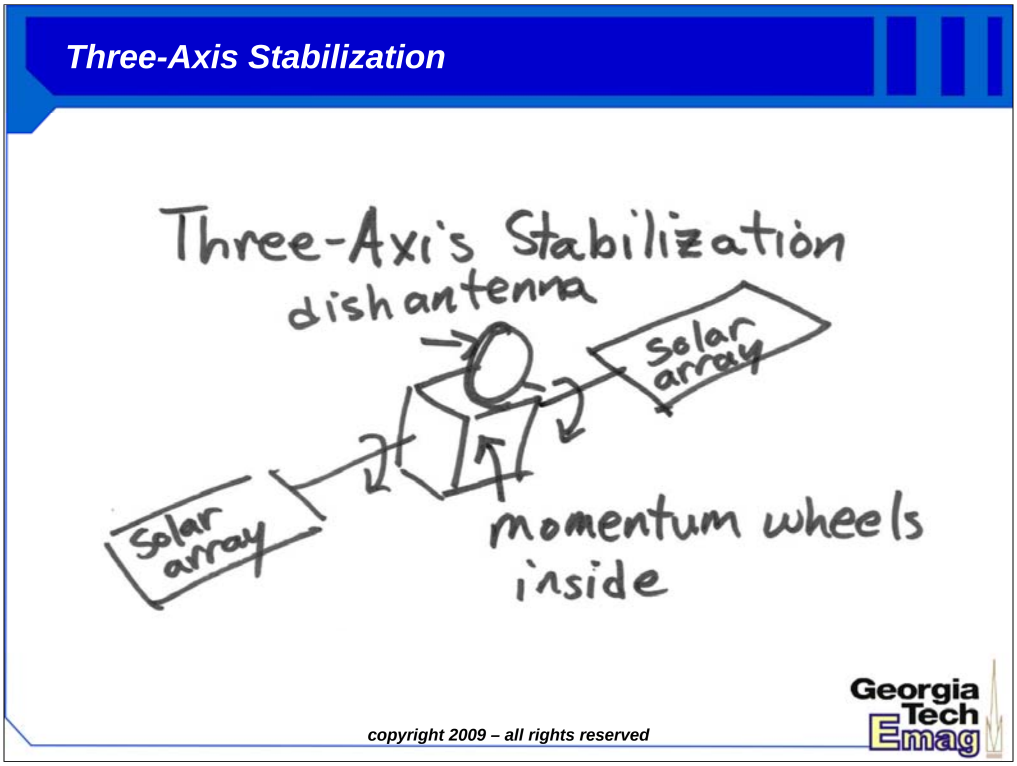
There are two types of positional controls in space. Orbital systems allow the satellite to make semi-regular corrections to its orbit. These are effectively ensuring that the (x,y,z) position of the satellite is appropriate. For example, GEO satellites make periodic thruster adjustments weekly to ensure that the position from a vantage point on earth remains stationary. Small liquid-fuel thrusters that can be turned on and off provide this service. Running out of this fuel is one of the key lifetime-limiting considerations of a satellite.

Attitude control involves the orientation of a satellite in space (pitch, yaw, and roll). This is particularly important for other systems to function correctly: the communications antennas must point towards the earth station or earth coverage area; the solar cells must point towards the sun. There are generally two types of attitude stabilization methods.

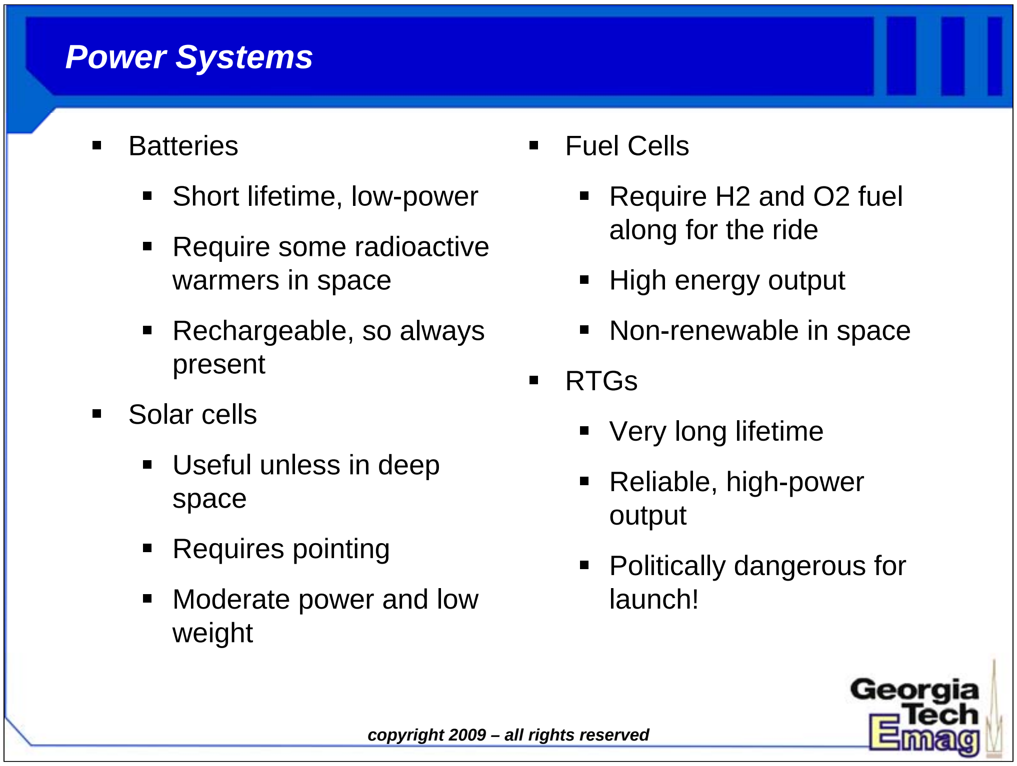


A “spinner” satellite is spun into orbit so that its gyroscopic forces keep the satellite from twisting into an undesired orientation. A communications antenna is typically “de-spun” so that it points towards earth even though the satellite is spinning. Sensors along the drum of the satellite use IR probing to makes sure the satellite antenna points to earth. Small thrusters along the drum can perform timed-fires for orbital control.

The drum of the spinner satellite is covered in solar cells to allow collection of electrical power from the sun. Unfortunately, only about 1/3 of the power is collected across the drum shaped body of this satellite compared to a comparably-sized flat-panel solar cell array.



Three-axis stabilized satellites use internal momentum wheels to stabilize its attitude. These satellites look like boxes with flat-panel solar arrays sticking out of them. The solar power collection on these satellites is much more efficient. The motors driving the momentum wheels offer a stable method for electronically controlling the attitude. Special mechanical considerations must be given to packaging this satellite in a rocket payload since the solar cell arrays must have a way to unfurl once in space.

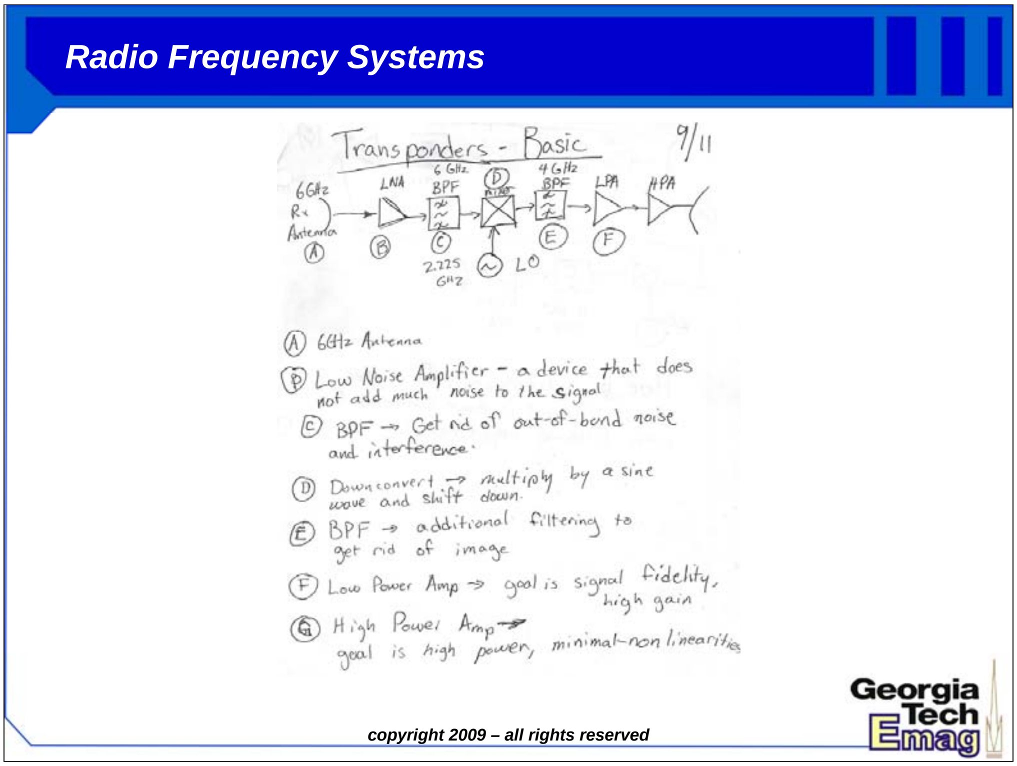


Batteries: They have stored energy, which is utilized by the spacecraft when required. Although this technology is well understood, reliable and consistent; it is just not powerful enough to meet the needs of a space mission. However, batteries can be used to store the energy created by some other means. Hence, batteries can be used for storing excess power on the relay satellite and for powering the three probes during their descent into Neptune.

Fuel Cells: These devices store hydrogen and oxygen in separate chambers. These two elements are then combined to form water and the resulting chemical reaction expends energy, which is harnessed into electrical energy. Fuel cells are used in several near-Earth missions and are similar to batteries except that they can be refueled and have a longer lifespan than batteries. However, they would require too much fuel for a project like Kepler. Moreover, they release a lot of heat in operation, which creates the added overhead of managing that heat. Thus, batteries will be preferred over fuel cells for this project.

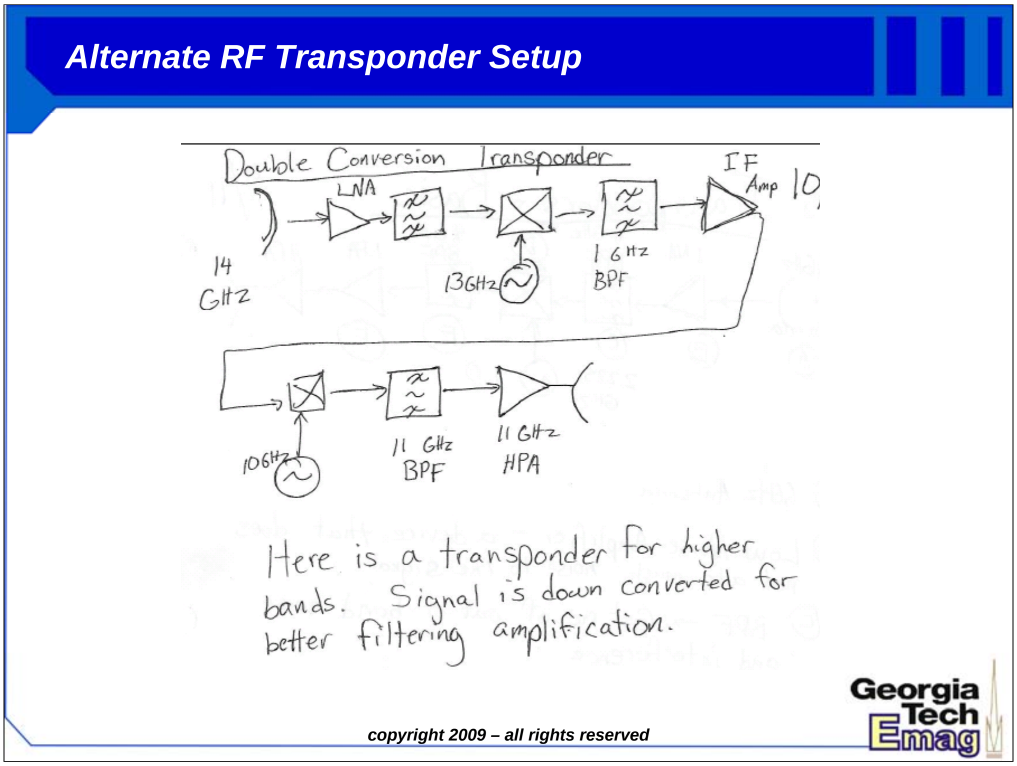
Solar Panels: They convert solar radiation into electricity and are extremely successful for missions close to the Sun. However, they are rendered useless when a spacecraft travels beyond the orbit of Mars and, hence, cannot be a viable source of energy near Neptune. Solar panels are large constructions and are extremely fragile. They are also very expensive. The costs do not justify the use of solar panels for the part of the mission where they can be used to produce electricity. Hence, solar panels will not be used in the Kepler mission.

4. **Radioisotope Thermal Generators (RTGs)**: These devices have radioactive materials as fuel that decays and releases heat energy, which is converted into electricity by the use of thermocouples. An RTG does not give out a huge amount of energy like fission and fusion reactions, but it does give a small amount of energy steadily over a long period of time. RTGs were used to power both the Cassini and the Galileo missions, and are extremely reliable and consistent.



Now let's turn to the RF and communications subsystems of a satellite. The simplest function of the satellite is to relay a signal back to earth. We refer to the RF system that accomplishes this as a transponder. Above is a block diagram sketch of basic "bent-pipe" transponder, which receives a signal from earth at 6 GHz, translates the analog system to 4 GHz, amplifies and transmits this translated signal back down to earth.

This is a very simple architecture, fundamentally analog, and can be used for a variety of signals, modulations, and protocols once in space – so it's very flexible. One drawback is that anyone can use it (and jam it)! Another problem is that the signal is not "cleaned up" –whatever noise and interference is present on the uplink will pass right on through to the downlink.



Above is a slightly more sophisticated version of our transponder, called a double conversion transponder. In this scheme, instead of translating an uplink signal directly to another downlink signal, the modulated carrier is passed down through a lower intermediate frequency through two mixing operations. In the example above, the uplink is at 14 GHz, the downlink is at 11 GHz and an intermediate frequency of 1 GHz is used to provide filtering and amplification. These operations tend to be much easier and less-costly to perform at lower frequencies.