Expanding the Internet Into the Universe

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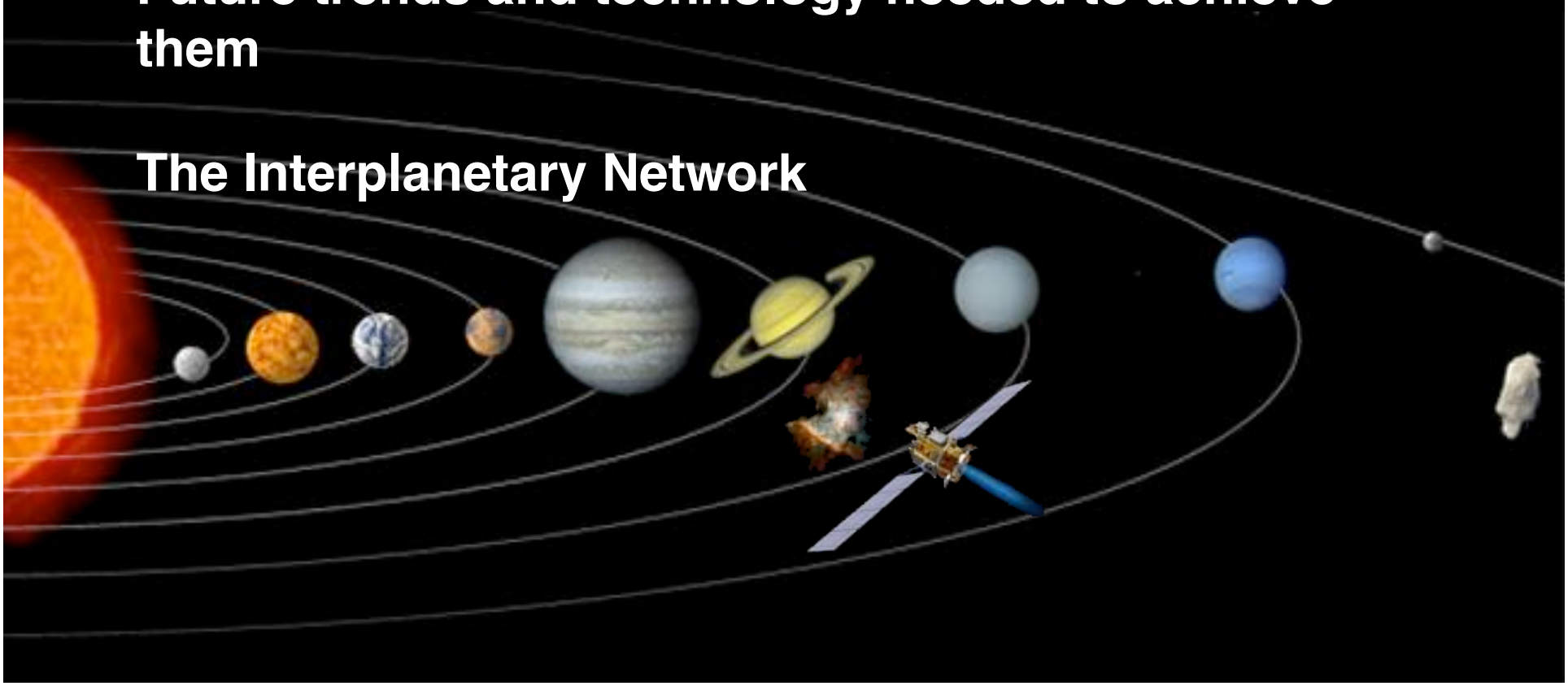
Agenda

Deep space missions

What makes Deep Space Communications harder?

Future trends and technology needed to achieve them

The Interplanetary Network



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Where is Deep Space?

I define "deep space" to be anything beyond lunar orbit

Things that are closer than deep space are easy – relatively speaking!

Our stuff is so far away we use a measure of distance call the "astronomical Unit" which is the average distance between the Earth and the Sun

- 1 AU ≈ 149,597,871 kilometers ≈ 93 million miles

Deep Space

Near Earth

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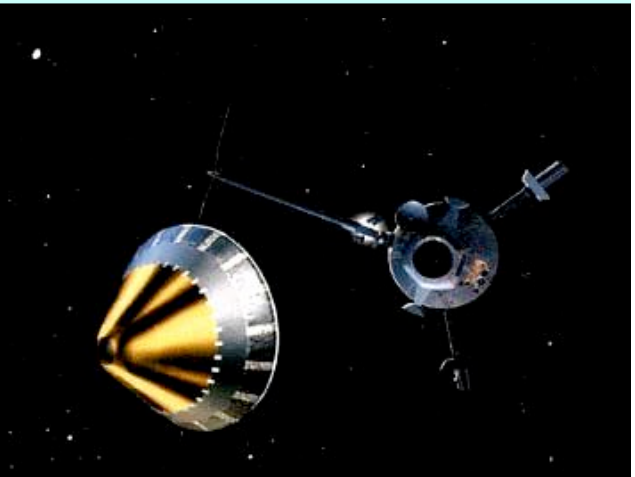
Some Current Deep Space Missions

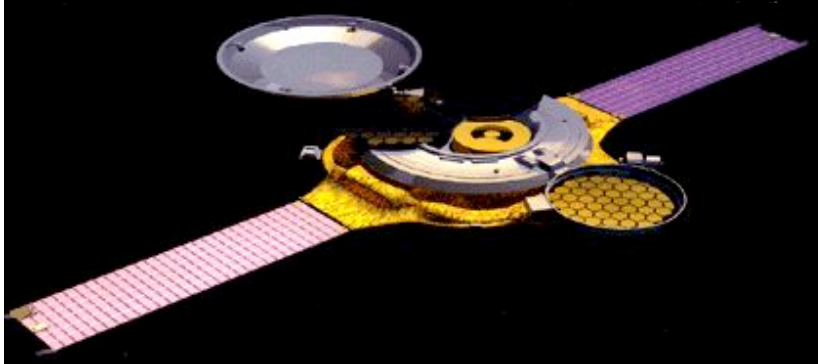
Voyager
- Searching for the edge of the Solar System

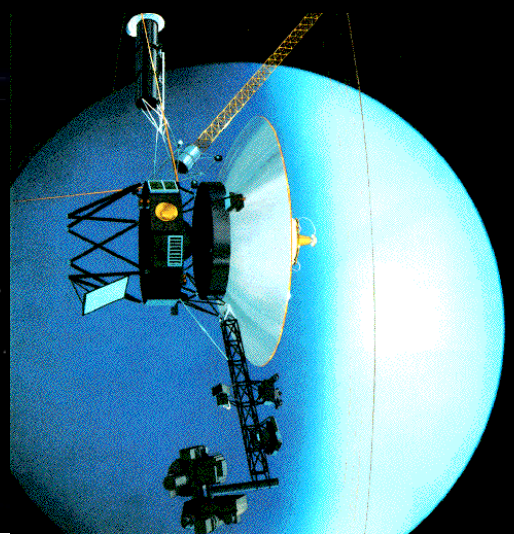
Galileo
- Detailed exploration of the Jupiter system

Ulysses
- Mission to the Sun

Genesis
- Return samples of solar wind







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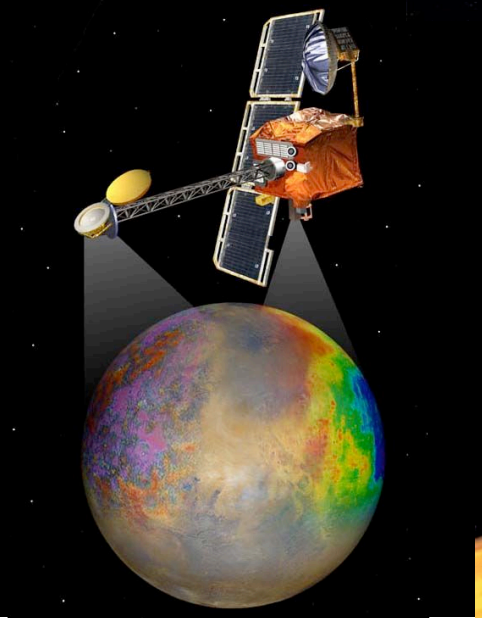
Some Current Deep Space Missions

- Mars Global Surveyor
  - Global mapping of Mars
- Stardust
  - Fly through a comet's tail and bring back its dust
- Mars Odyssey
  - More detailed exploration from orbit
- Mars Exploration Rover 1 (hopefully)
  - Explore Mars surface and look for evidence of water



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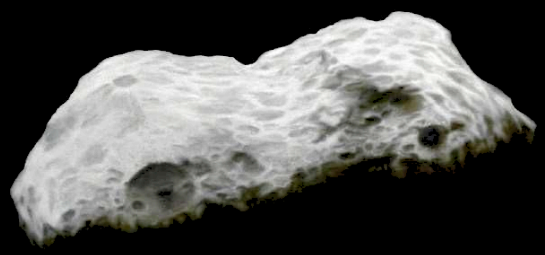
Some Future Deep Space Missions

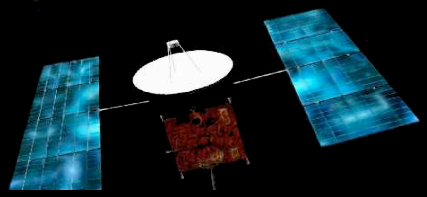
Mars Program
- Orbiters, Landers, Sample Return
- Multiple missions each opportunity
- International missions

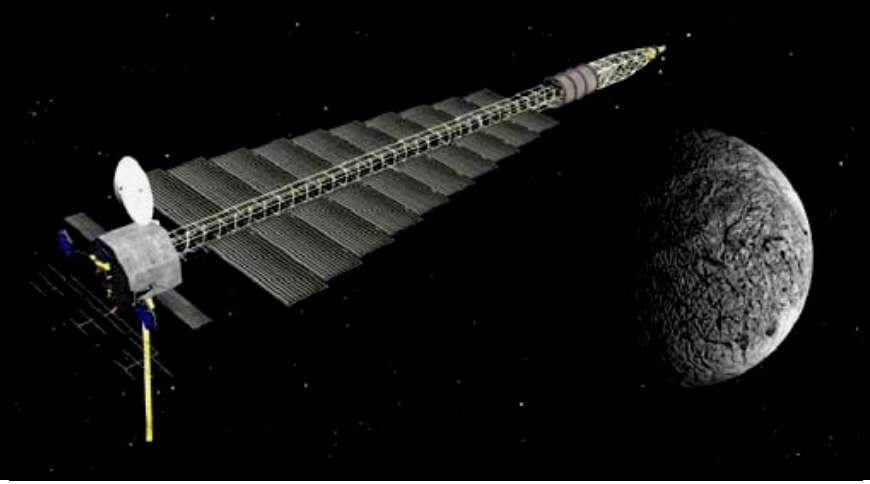
MUSES-C (Japan)
- Return samples from a comet

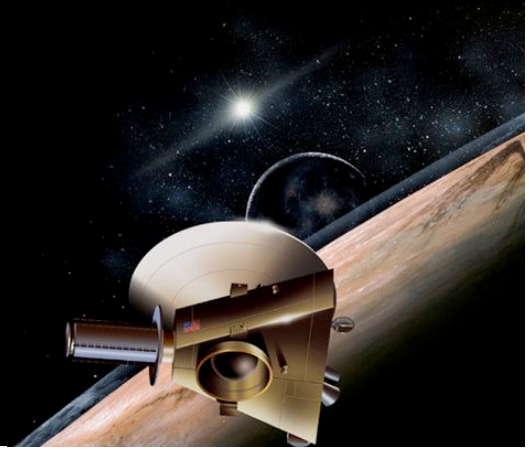
New Horizons (JHU-APL)
- Explore Pluto and Kuiper Belt objects

Jupiter Icy Moon Orbiter (JIMO)
- Study Jupiter's moons in great detail









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Some Future Deep Space Missions

Space Infrared Telescope Facility (SIRTF)

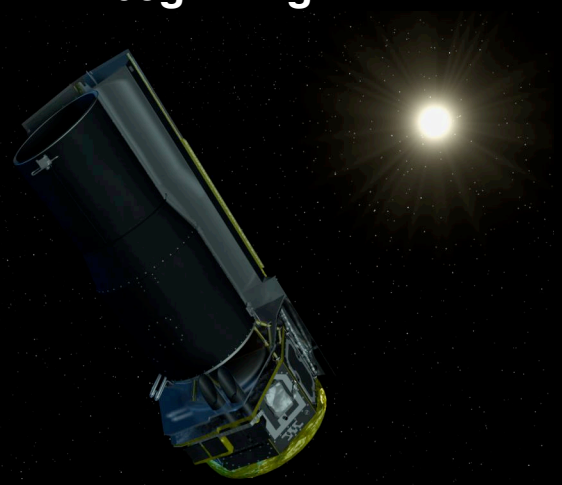
Study the universe in the infrared

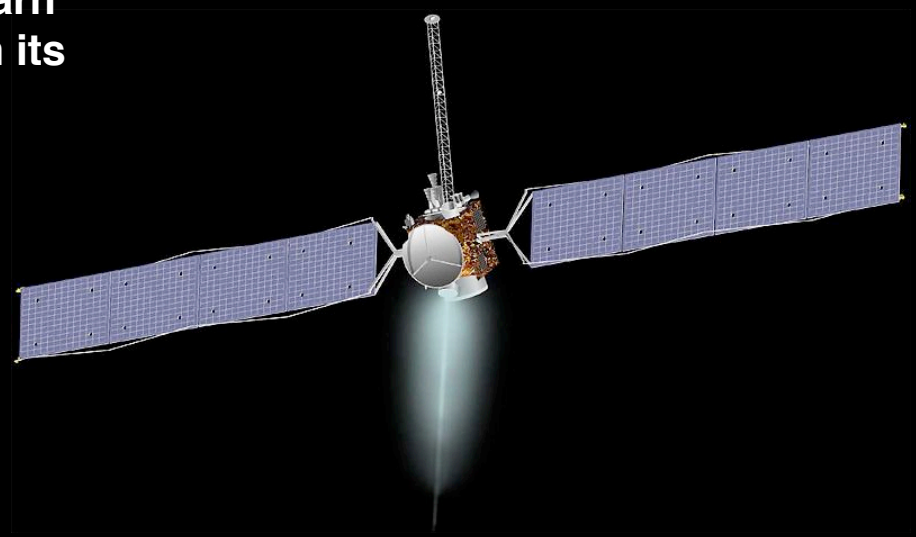
Deep Impact

Shoot a projectile at a comet and study the material that is ejected

DAWN

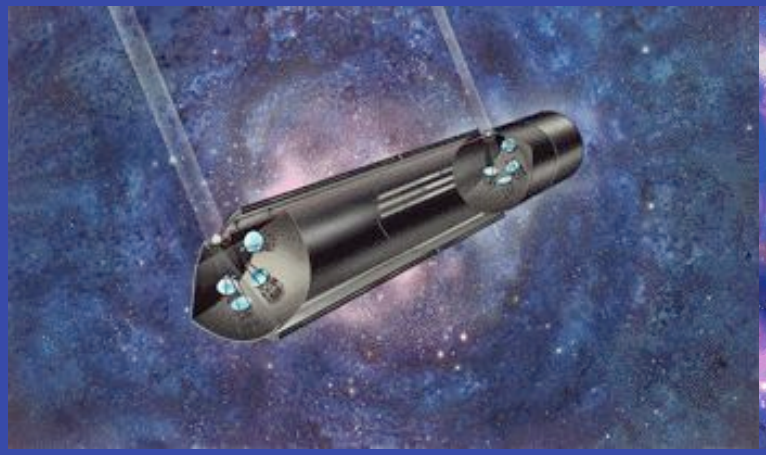
Study two large asteroids to learn how the solar system looked in its beginning





Space Interferometer Mission (SIM)

- Optical interferometer in space
- Will directly detect other planetary systems



Terrestrial Planet Finder (TPF)

- Several free-flying spacecraft working together
- Large space space interferometry
- Will study chemical composition of planets in other solar systems

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Anatomy of a Cruising Deep Space Craft

- Spacecraft sent to deep space are complex systems
- They must survive in extreme environments
  - Temperature
  - Acceleration
  - Radiation
- They have to be extremely reliable – sometimes lasting decades without the ability for repair
  - Redundant systems
- They must operate with some degree of autonomy
- Notice that the communications system is huge compared to the overall size of the spacecraft

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Definitions: Uplink and Downlink

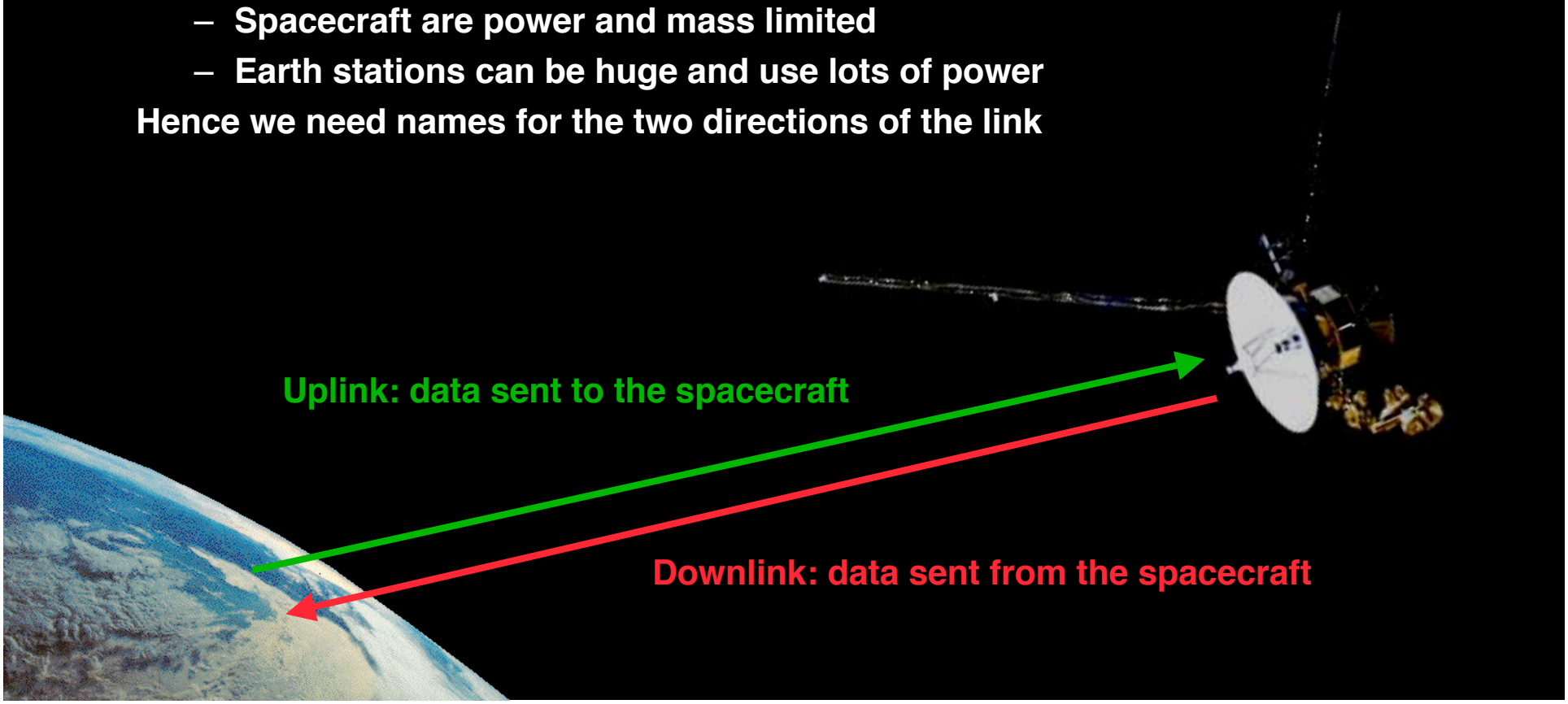
Most terrestrial person-to-person communications (including amateur radio) links are pretty symmetric

- Both ends have similar equipment
- Both directions have similar performance

The communications link to deep space is highly non-symmetric

- Spacecraft are power and mass limited
- Earth stations can be huge and use lots of power

Hence we need names for the two directions of the link



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Why is Communications Hard? Lots of Signal Loss

Communications performance decreases as the square of the distance.

Jupiter is nearly 1 *billion* km away, while a GEO Earth communications satellite is only about 40 *thousand* km away

- It's about 87 dB (~1 billion times) harder from deep space!

A person with a loud voice and good hearing, standing in front of NASA headquarters in Washington, can talk with a friend a block away. Deep space communications would be like trying to talk with the same friend in Boston!

Communication Latency

It takes a long time (five minutes to 12 hours) for communications signals to travel between a deep space spacecraft and the Earth

Deep space missions must be more autonomous than Earth orbiters

- Critical events, like trajectory changes or flyby science acquisition, are planned in advance and programmed into the spacecraft's computer

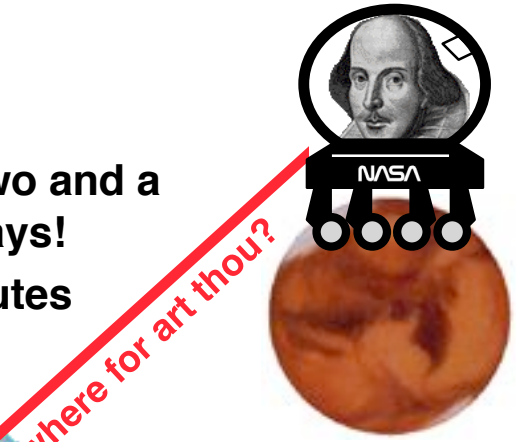
Spacecraft reaction to anomalous events must occur autonomously

The information sent from Earth to deep space is generally not used for real-time control

Signal Latency:

With half the actors on Earth and other half on Mars, Shakespeare's *Romeo and Juliet* would take over two and a half days to complete! At Pluto, it would take 187 days!

Signal time from Mars to Earth = 4.4 minutes
Signal time from Pluto = 5.3 hours



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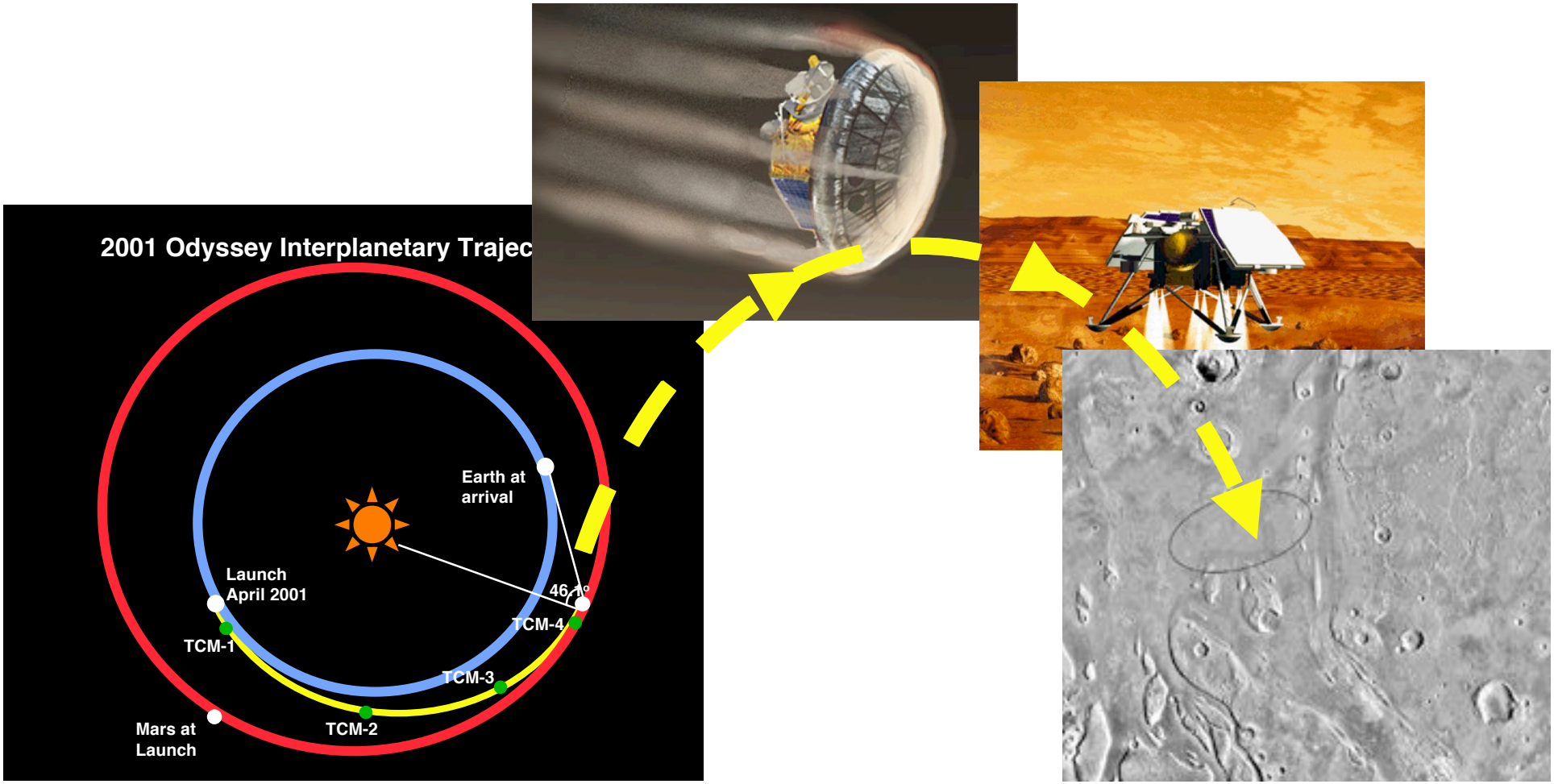
The Challenge of Deep Space Navigation

- Deep space missions use communications link to help perform navigation
- Very accurate positions need to be known over very large distances
- Also must "navigate" the target bodies!



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The Deep Space Network (DSN)

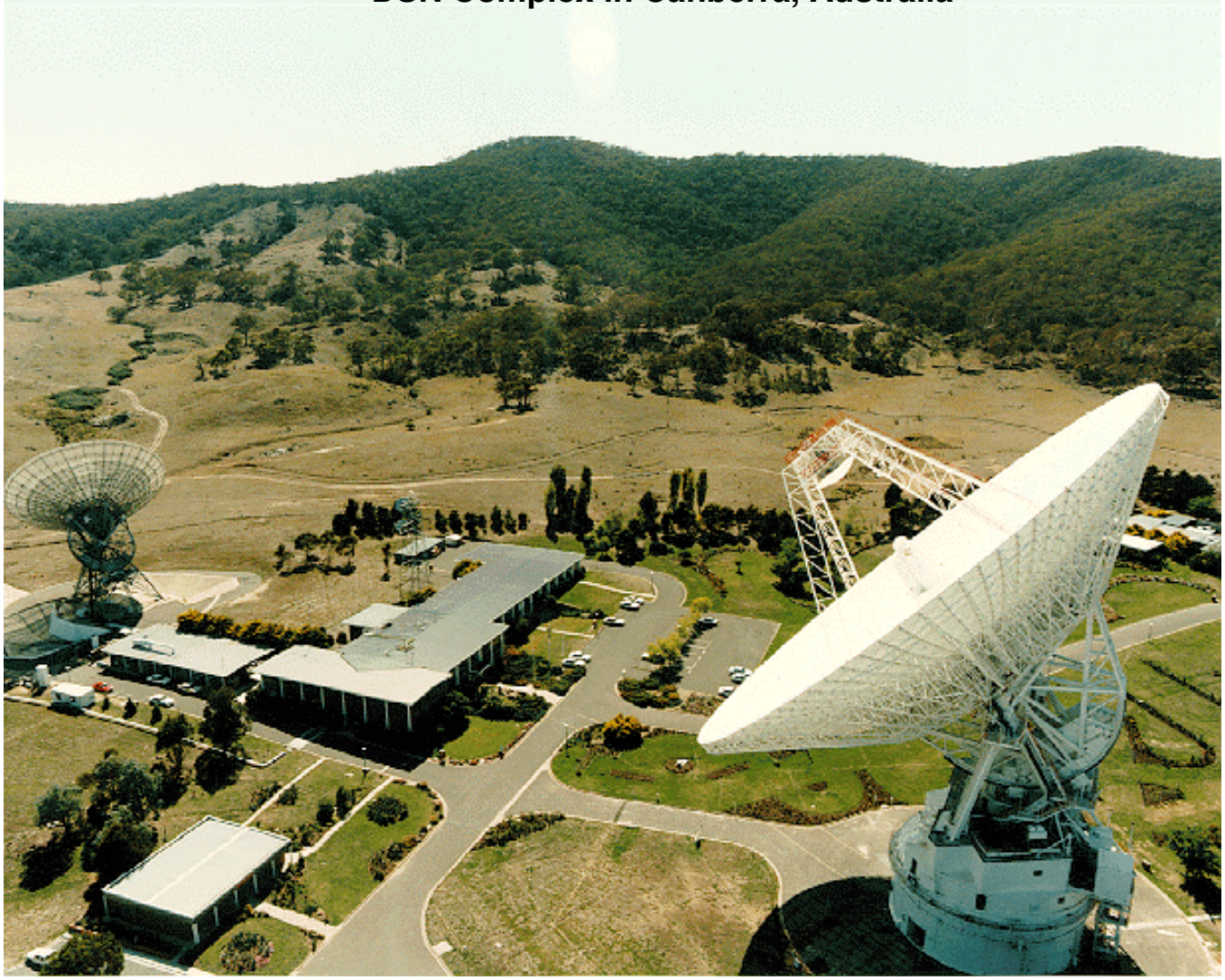
A unique national asset for communicating with deep space

Three "complexes" around the Earth so that continuous contact is possible

- Goldstone, California
- Madrid, Spain
- Canberra, Australia

Antennas from 26m to 70m in diameter

DSN Complex in Canberra, Australia



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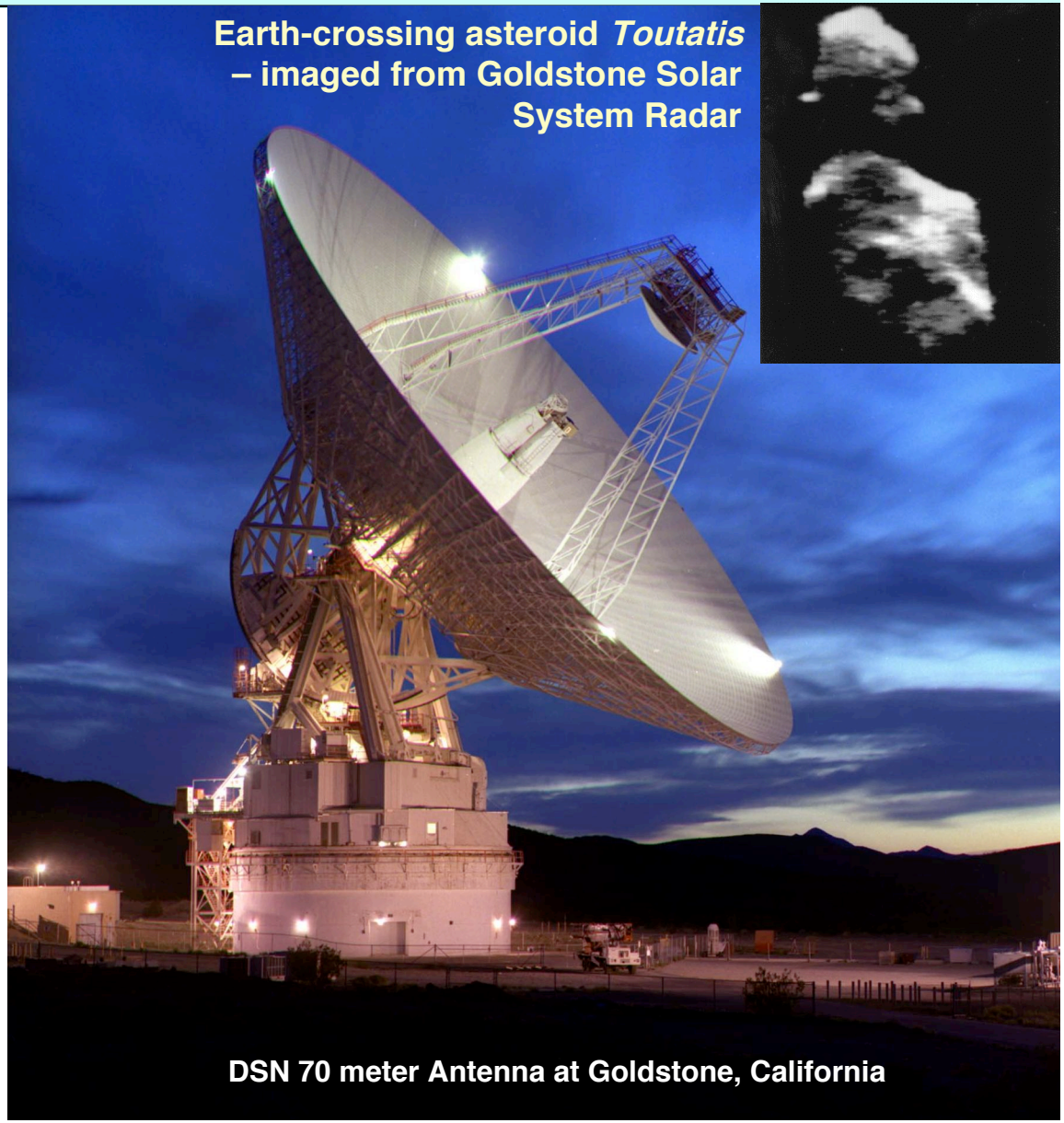
DSN 70m Antennas

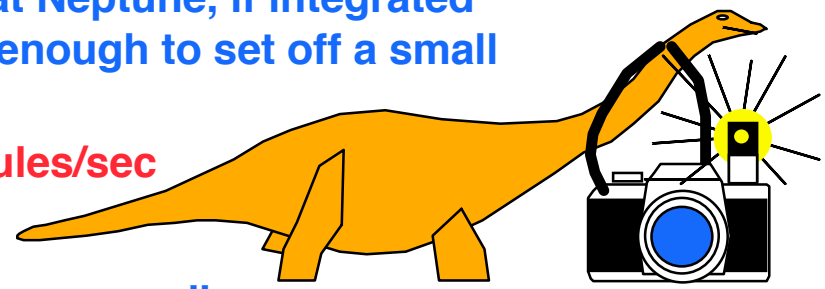
- Largest steerable communications antennas in the world
- Goldstone Solar System Radar for imaging Earth-Crossing Asteroids & mapping orbital debris
- Communications with interstellar spacecraft - Pioneer 10 and Voyagers
  - Nearly 88 AU (about 8 billion miles)
  - Signals take ~24 hours to get to Voyager 1 and back



Received Signal Sensitivity:

The received energy from Voyager at Neptune, if integrated for 300 million years, would be just enough to set off a small photographic flashbulb!

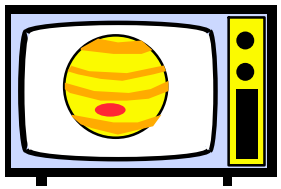
Received power = 10^{-17} Joules/sec



Command Power:

The DSN puts out enough power in commanding Voyager that it could easily provide high quality commercial TV at Jupiter!

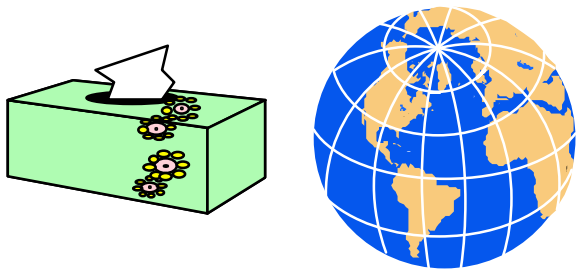
Transmitted power = 400 kW



Dynamic Range of the DSN:

The ratio of the received signal power to the DSN transmitting power is like comparing the thickness of a sheet of tissue paper to the entire Earth!

Ratio = 10^{27}



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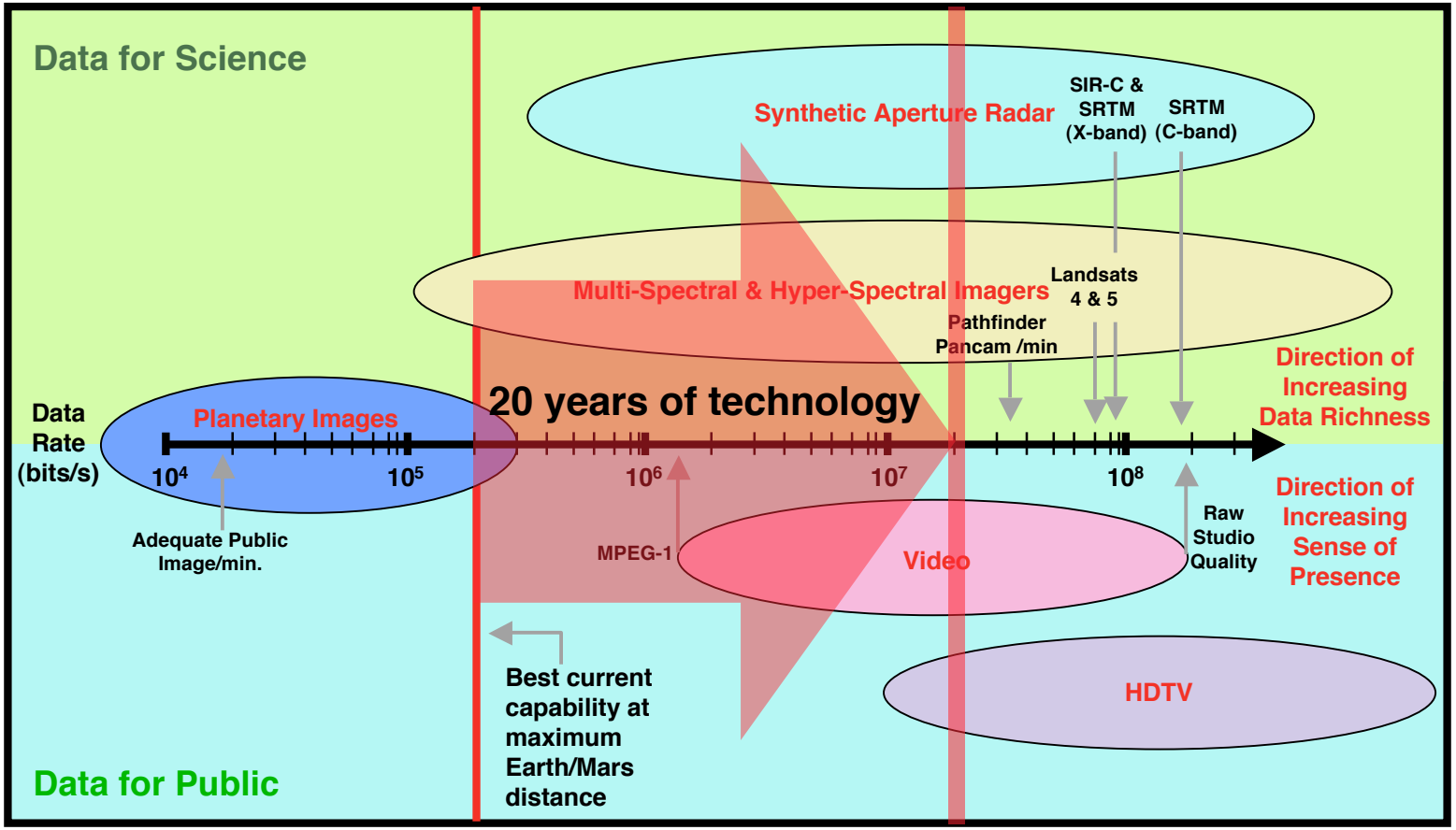
Trend: Increasing Downlink Data Rates

Increasing data rate for deep space will remain the focus for major investment over the next decade.

Data rate requirements for science and the public are factors of 10 to 100 higher than can be provided with the present spacecraft and the DSN.



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Trend: Increasing "Uplink" Data Rates

As spacecraft become more autonomous, they require more data

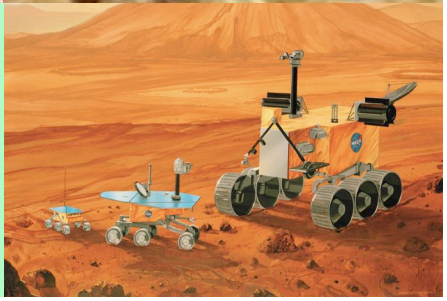
- Frequent reprogramming of spacecraft software
- Terrain maps and GPS-like data
- Sharing data with other spacecraft

When people venture into deep space, they will require lots more uplink

Cruise Missiles → • Guidance with on-board terrain maps

UAVs → • Guidance with GPS-like beacon aids

UGVs → • Stereoscopic vision
• Terrain classification



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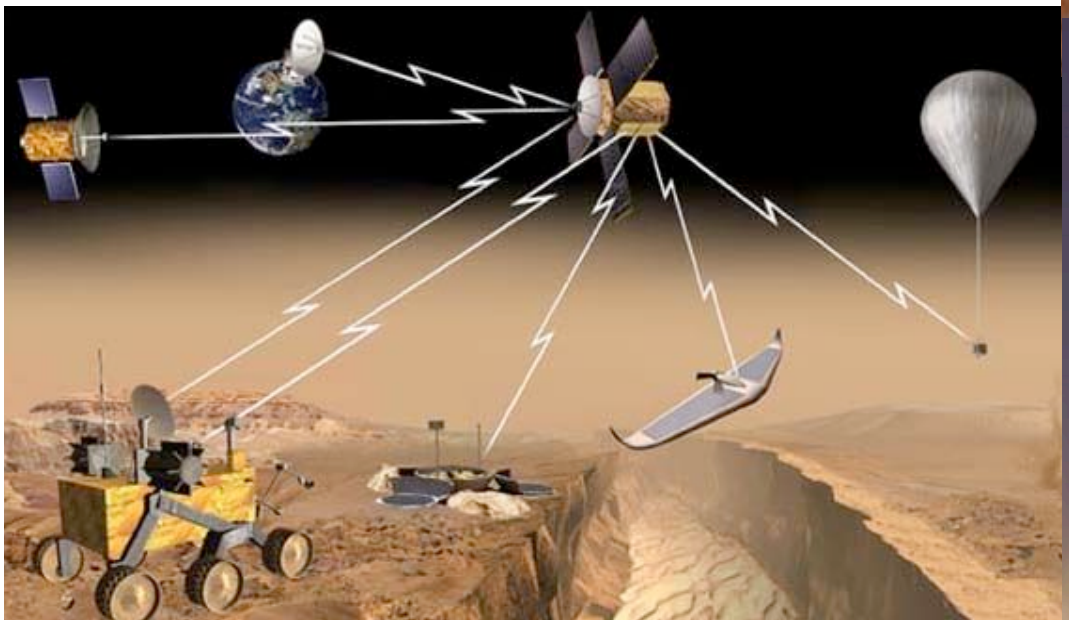
Trend: Missions with Multiple Spacecraft

The "point-to-point" assumption is going away.

Space exploration will be accomplished, more and more, by cooperating spacecraft.

- Planetary rovers supported by orbiters
- Cooperating rovers
- Complex missions (like sample returns) that involve launch and rendezvous of multiple spacecraft
- Sensor arrays, including interferometers



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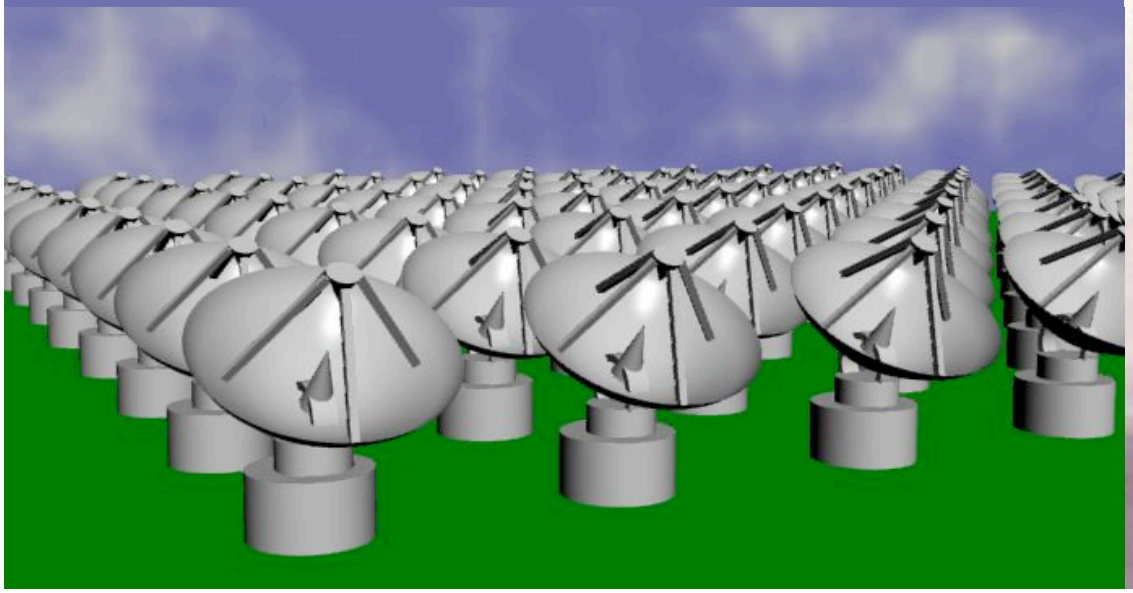
Key Technologies: Ka-Band Communications

- The higher the communications frequency, the narrower the beam and the better the performance
- We are moving to from 8.4 GHz (X-band) to 32 GHz (Ka-band)
- Theoretically we get the square of the ratio in improvement (a factor of ~16)
- However, increased atmospheric effects and more challenging antenna smoothness and pointing will result in a factor of about 4
- We are also studying large arrays of antennas



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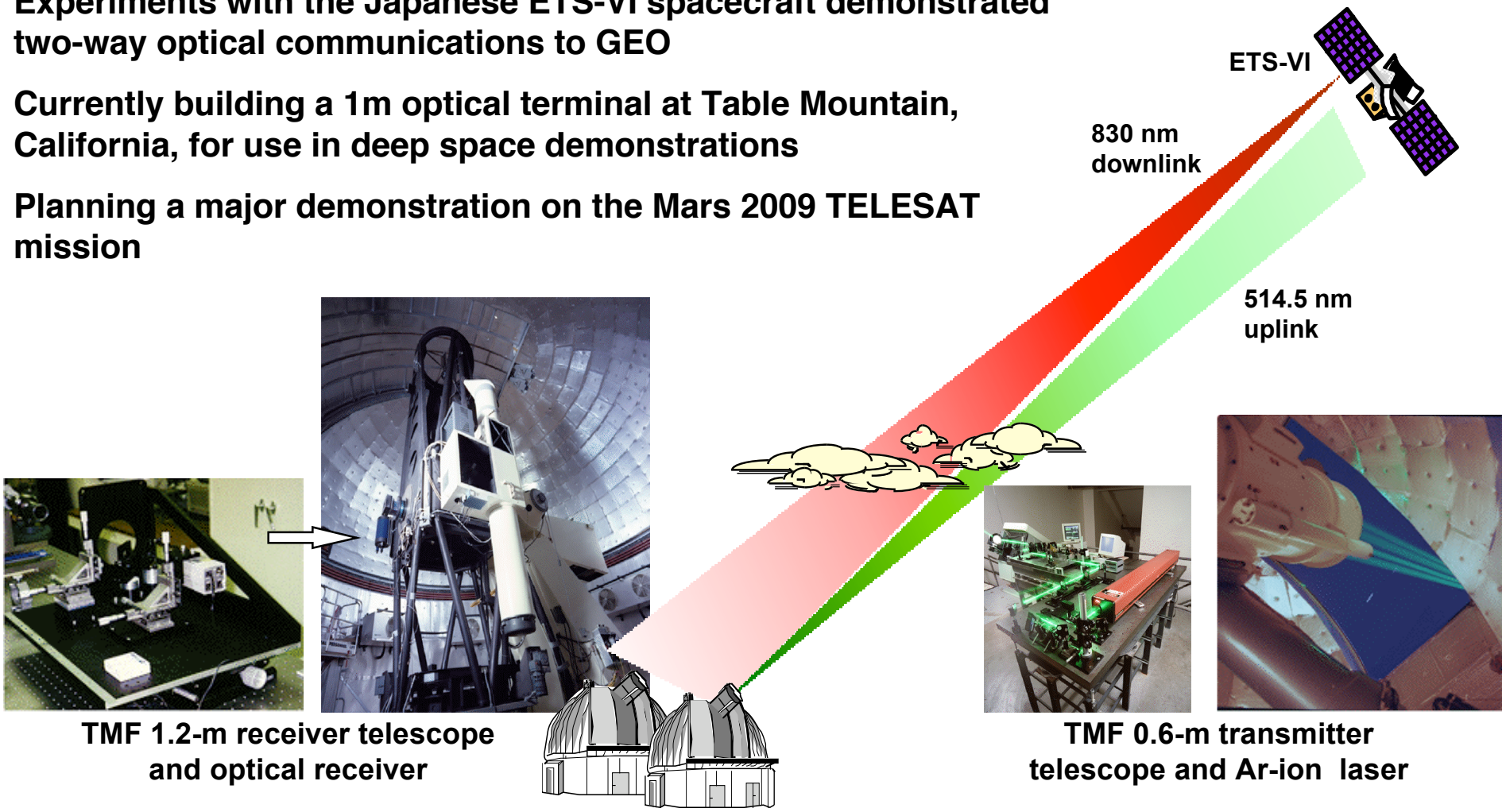
Key Technologies: Optical Communications

Optical communications offers further increases in deep space communications capability in a small, lightweight flight package

Experiments with the Japanese ETS-VI spacecraft demonstrated two-way optical communications to GEO

Currently building a 1m optical terminal at Table Mountain, California, for use in deep space demonstrations

Planning a major demonstration on the Mars 2009 TELESAT mission



TMF 1.2-m receiver telescope and optical receiver

TMF 0.6-m transmitter telescope and Ar-ion laser

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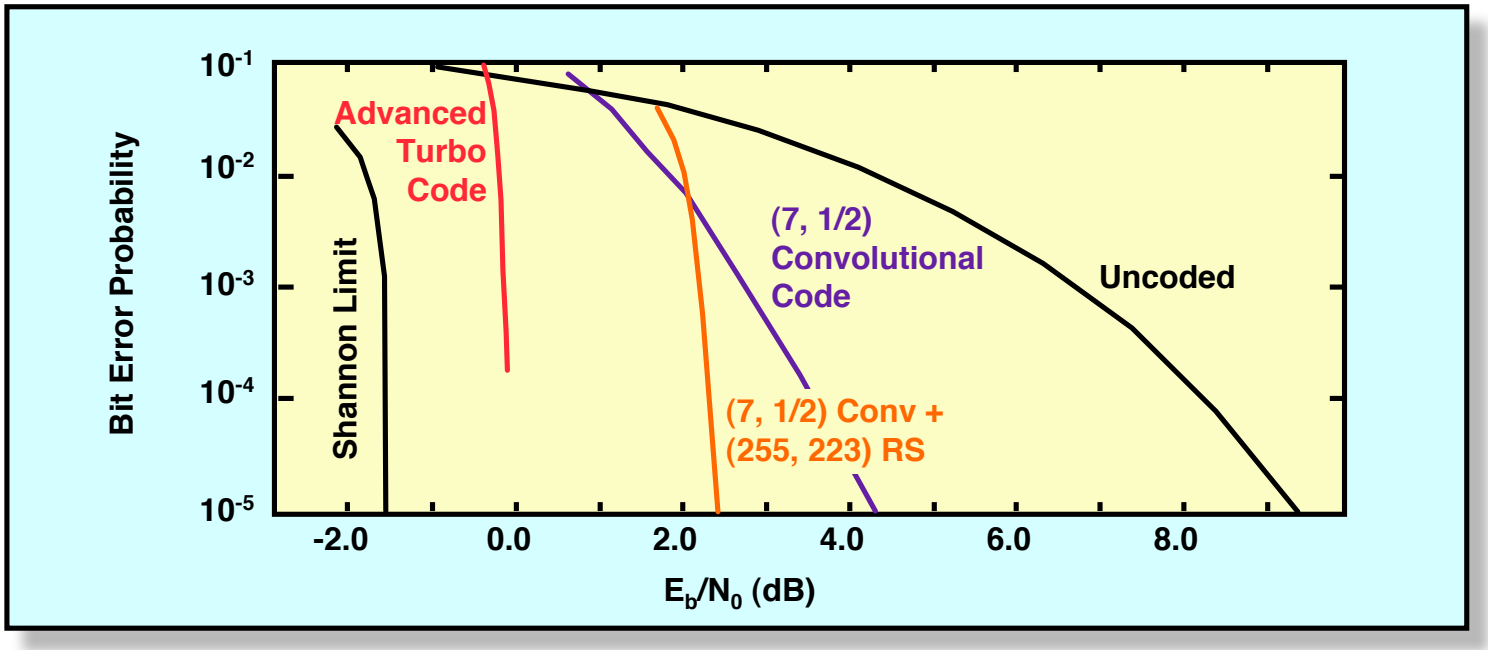
Key Technologies: Errer-correcting Kodes

Error-correcting codes add redundant information to the data stream so that the link can recover from a certain number of bit errors

NASA pioneered the application of these codes

They care now used by everyone in everyday life

More advanced codes could give us another factor of ten in performance



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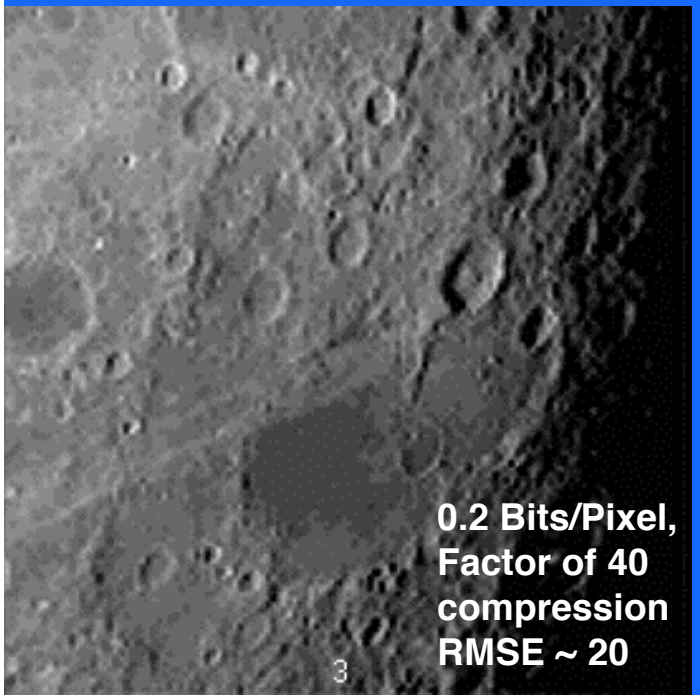
Key Technologies: Data Compression

We get equivalent performance gains by reducing the number of bits that must be sent – data compression.

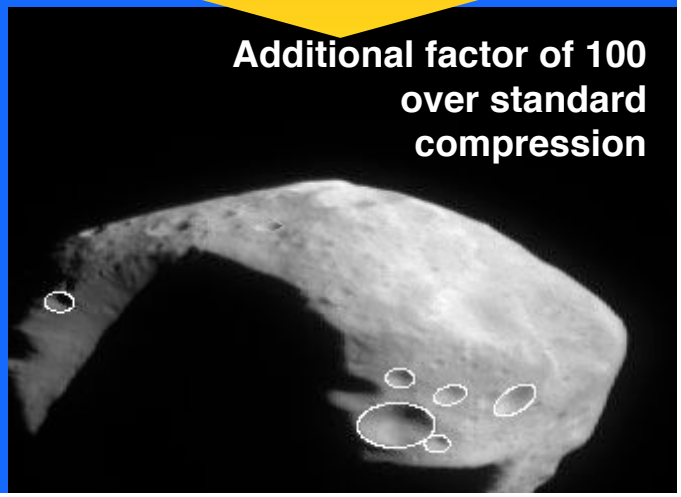
Today we use similar techniques to those used over the Internet

- These are fine-tuned to preserve the science content of the data

In the future we will combine these with artificial intelligence to help decide what is interesting BEFORE it is transmitted



Combine feature extraction & compression



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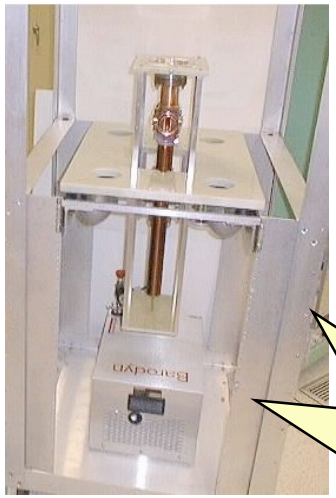
Key Technologies: Ultrastable Clocks

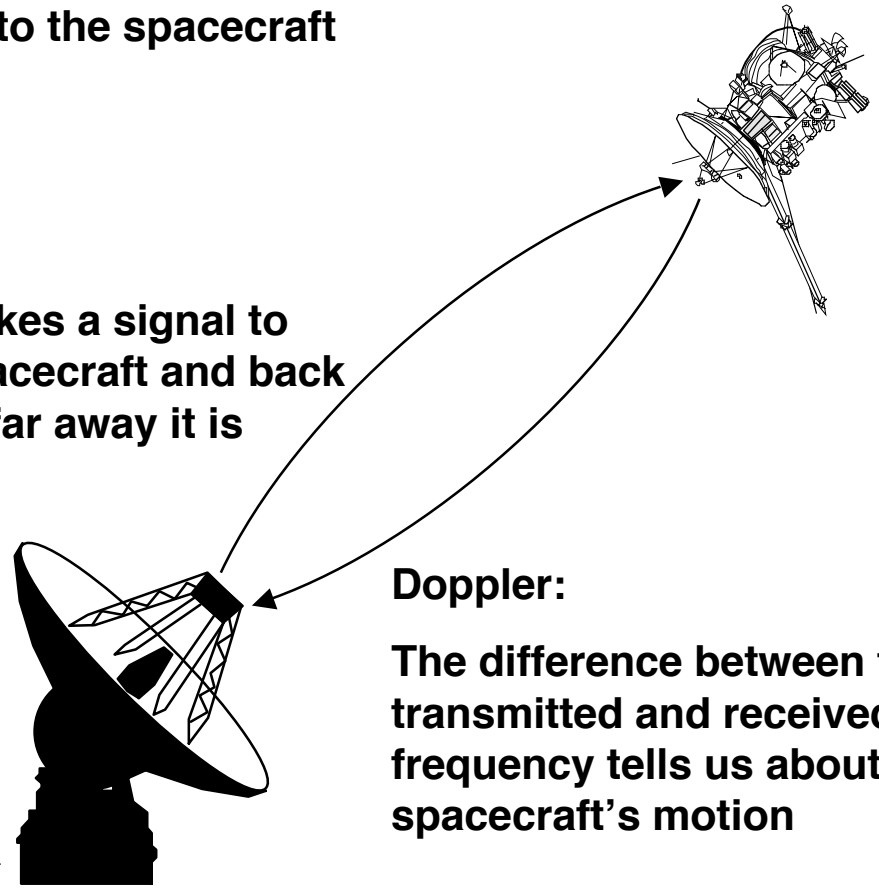
In order to navigate our spacecraft, we need the world's most accurate and stable clocks

Ionic clocks provide stability better than a part in 10^{16} for deep space round trip light times are already in the DSN

This technology will be migrated to the spacecraft



Trapped Ion
Frequency Standard



Ranging:

The time it takes a signal to get to the spacecraft and back tells us how far away it is

Doppler:

The difference between the transmitted and received frequency tells us about the spacecraft's motion

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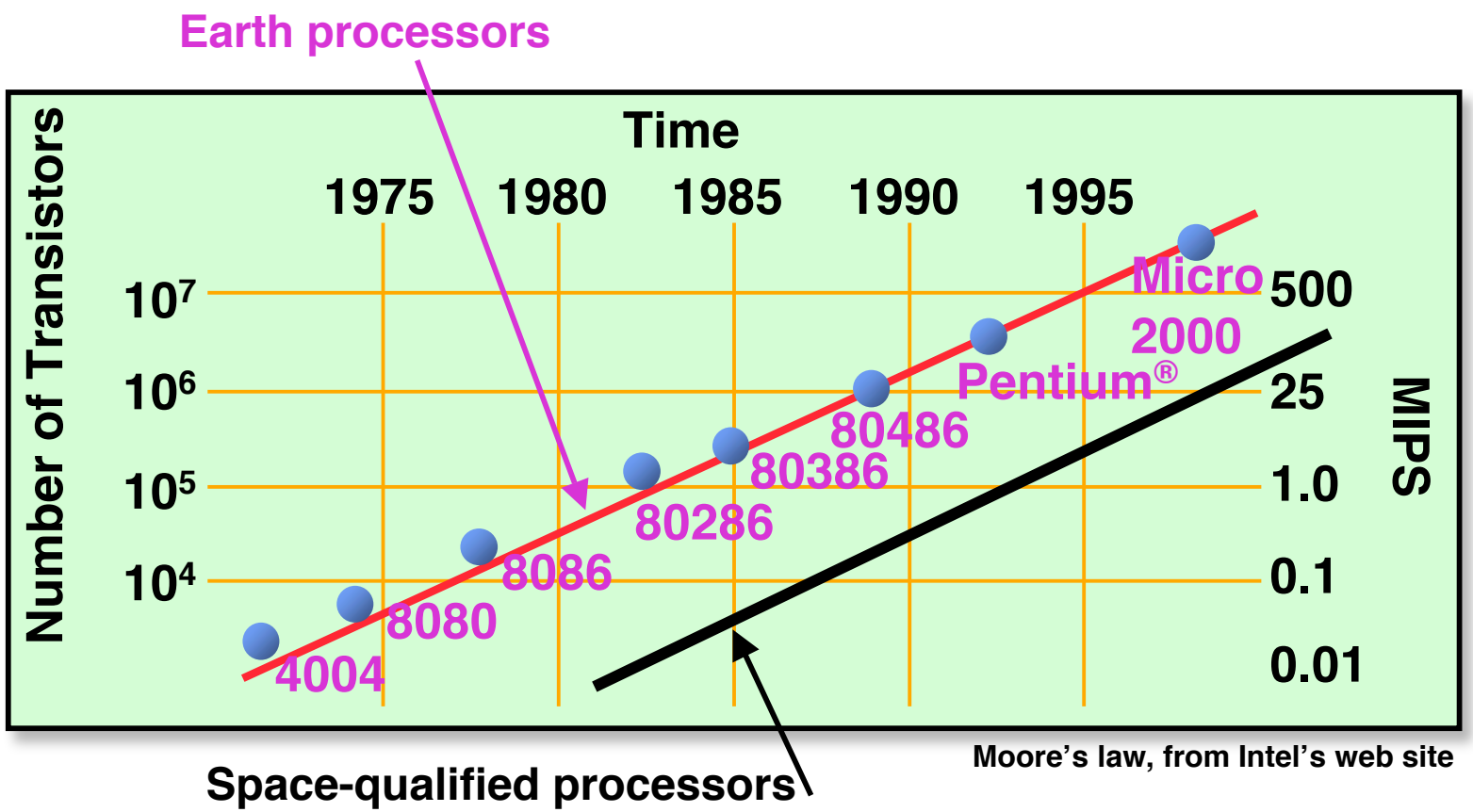
Key Technologies: Spacecraft Computers

Spacecraft hardware must survive in extreme environments

We cannot use commercial microprocessors. We must redesign and remanufacture them

Spacecraft hardware must be "ready to go" three years before launch

We end up flying computers that are three generations obsolete!



Moore's law, from Intel's web site

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Key Technologies: Internet-Like Protocols

The Internet does a few things that a very attractive to the problem of deep space communications

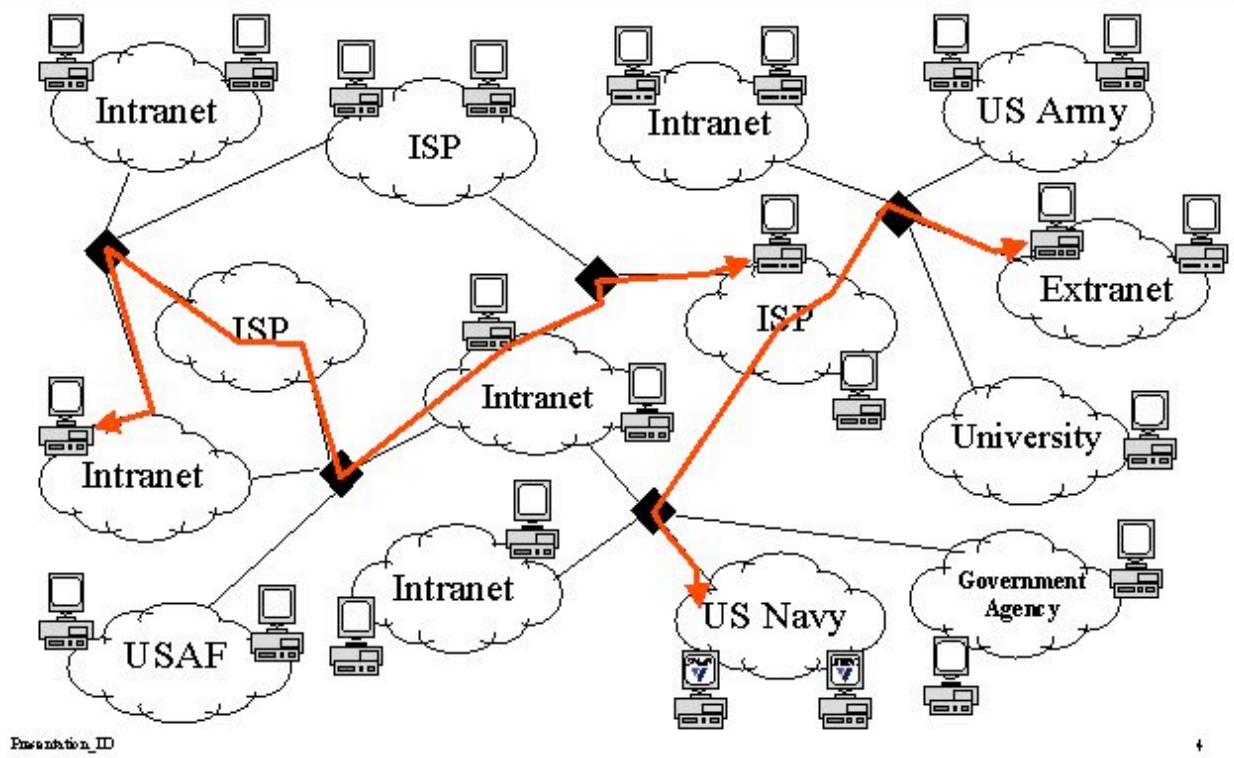
- Routing between nodes is handled automatically and dynamically depending on "visibility" and "availability"
- Data is transferred completely and with guaranteed quality (albeit with delays!)

Unfortunately, Internet protocols will not work with the long delays from deep space

- In fact, it does not work well with Earth-orbiting satellites

We are developing special sets of protocols that will work with the long delays

We will use standard protocols for shorter links, like those between Mars rovers and Mars orbiters



Interplanetary Network Directorate

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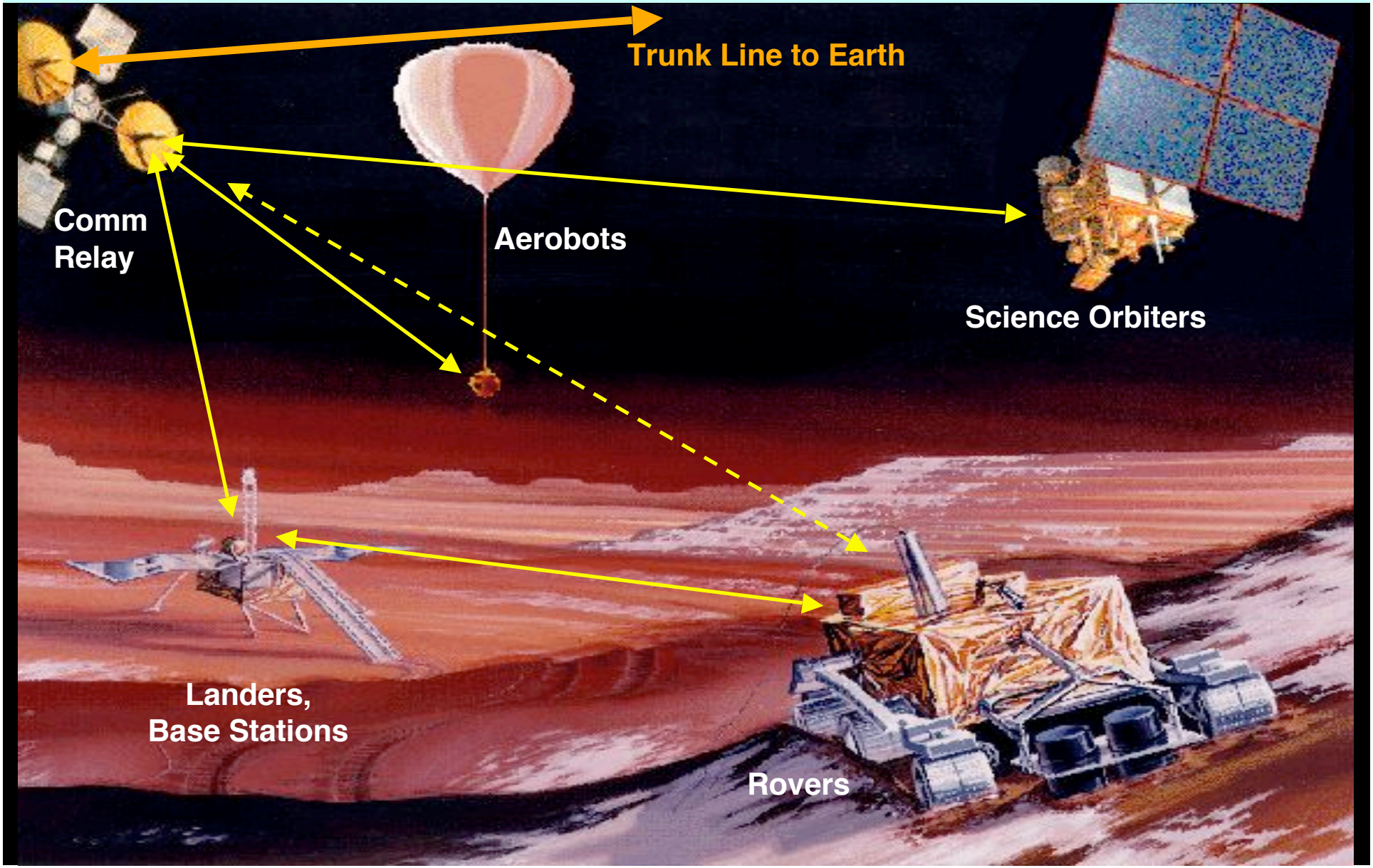
Setting Up Local Internets at Planets – Mars First

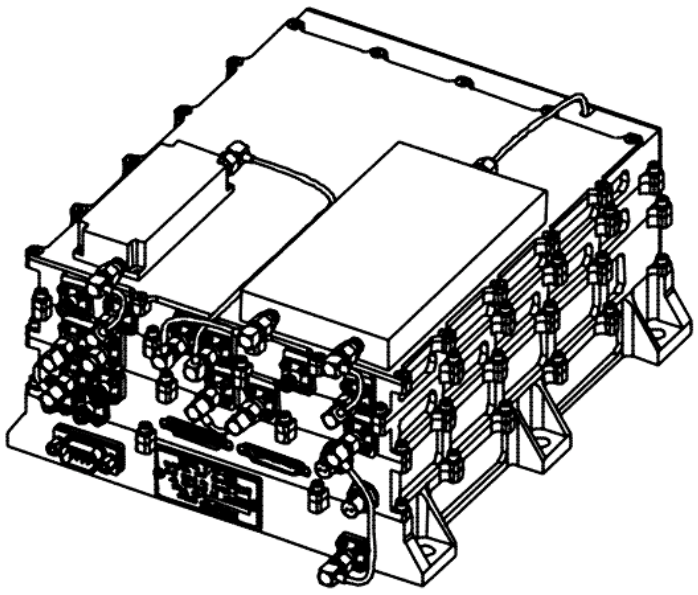


One of the reasons the Internet works is that there are standards

Lots of companies build stuff for the Internet and it all works together

We are developing the standards for the Interplanetary Internet

For the Mars Network, we are even building a standard modem



Electra UHF Transceiver

Planetary Networks

Will also provide GPS services

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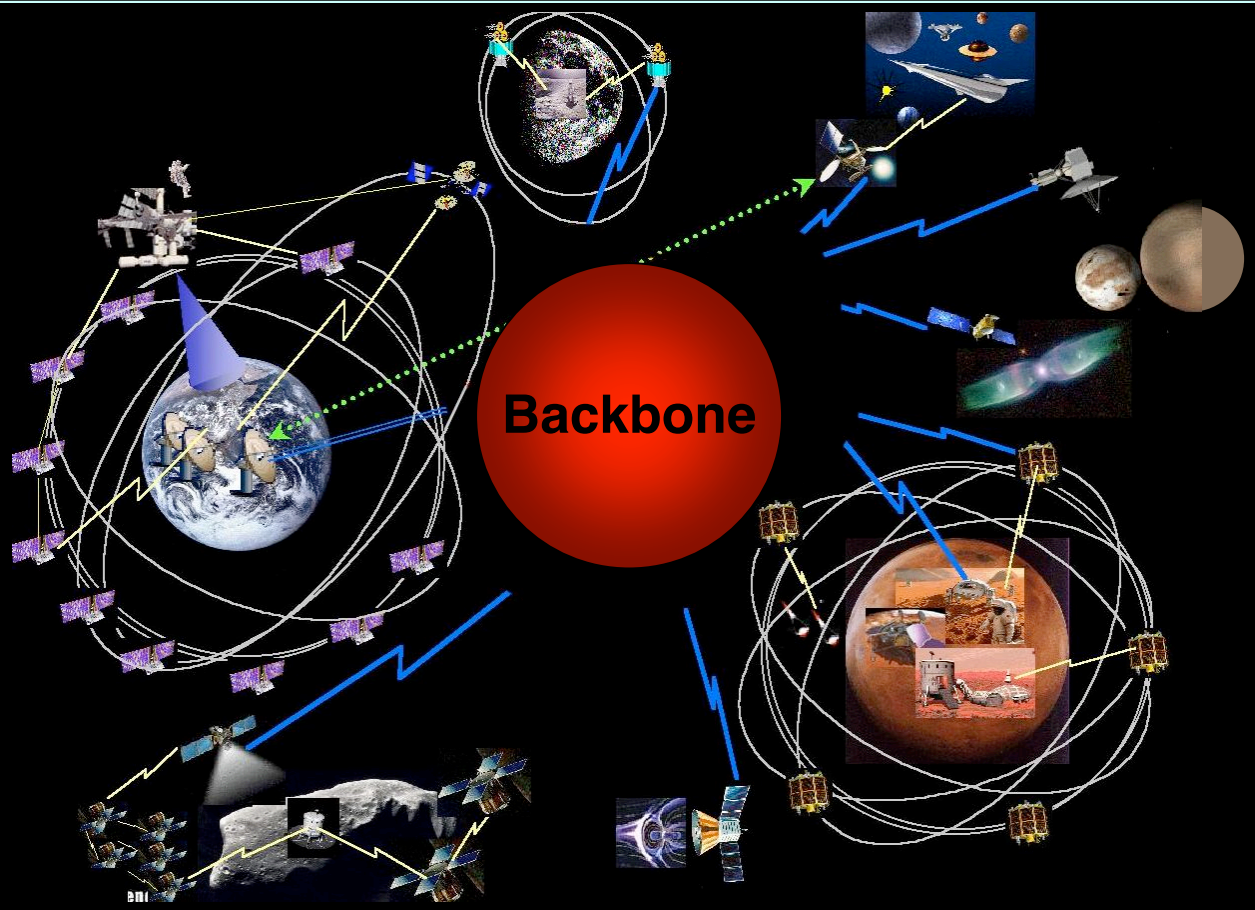
The Long-Term Future



"Planetary local networks" support targets of interest throughout the Solar System

- Network components are standardized and "cheap"
- Communications costs are a fraction of what they are today

A highly-capable backbone interconnects the planetary local networks

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Beyond the Solar System

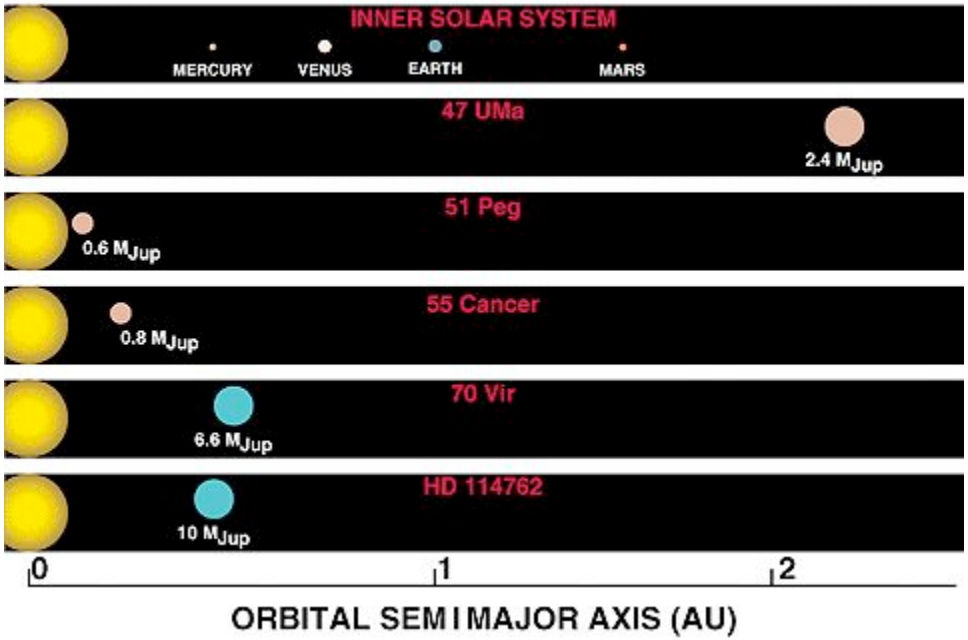
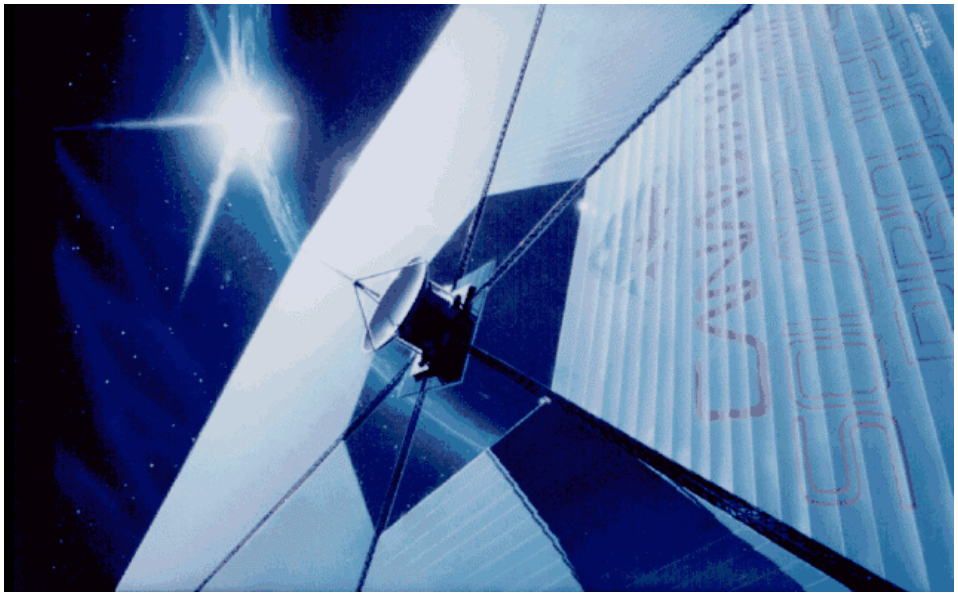
Up until six years ago, there were no known planets other than our Solar System's nine

Now there are 107 planets in 93 solar systems that have been discovered – most known planets are outside our own Solar System!

JPL is building spacecraft that can image some of these planets from our own Solar System and study their atmospheres

- This will tell us which ones might have life

JPL has been studying interstellar missions that could visit some of these planets

- Will travel up to 40 light years

How will the Internet work with a 40-year delay?