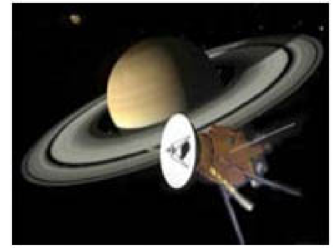
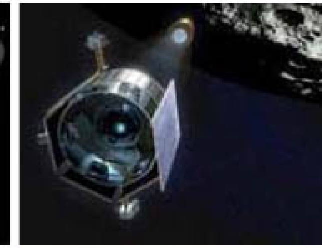
Jet Propulsion Laboratory
California Institute of Technology

Interesting Problems in Deep Space Communications

Dr. Les Deutsch
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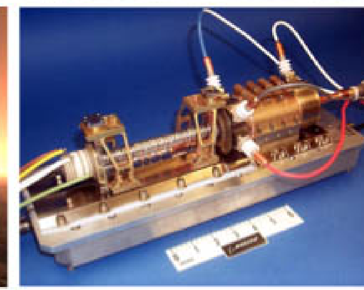

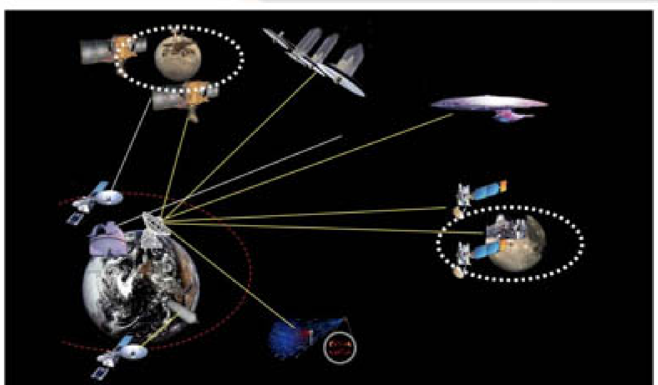
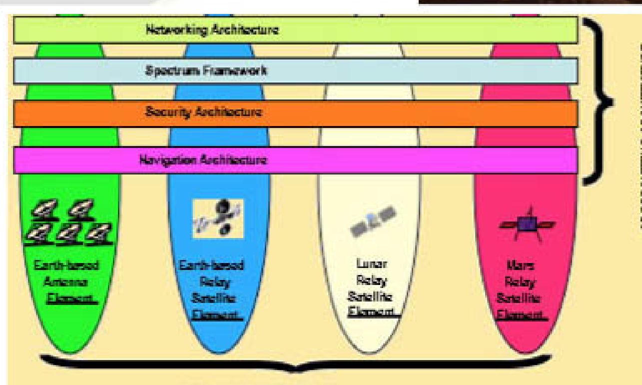

Agenda

- What makes deep space unique?
- Case study 1: Galileo mission to Jupiter
- Case study 2: Cassini/Huygens mission to Saturn
- Future trends in deep space communications
- What worries me today?

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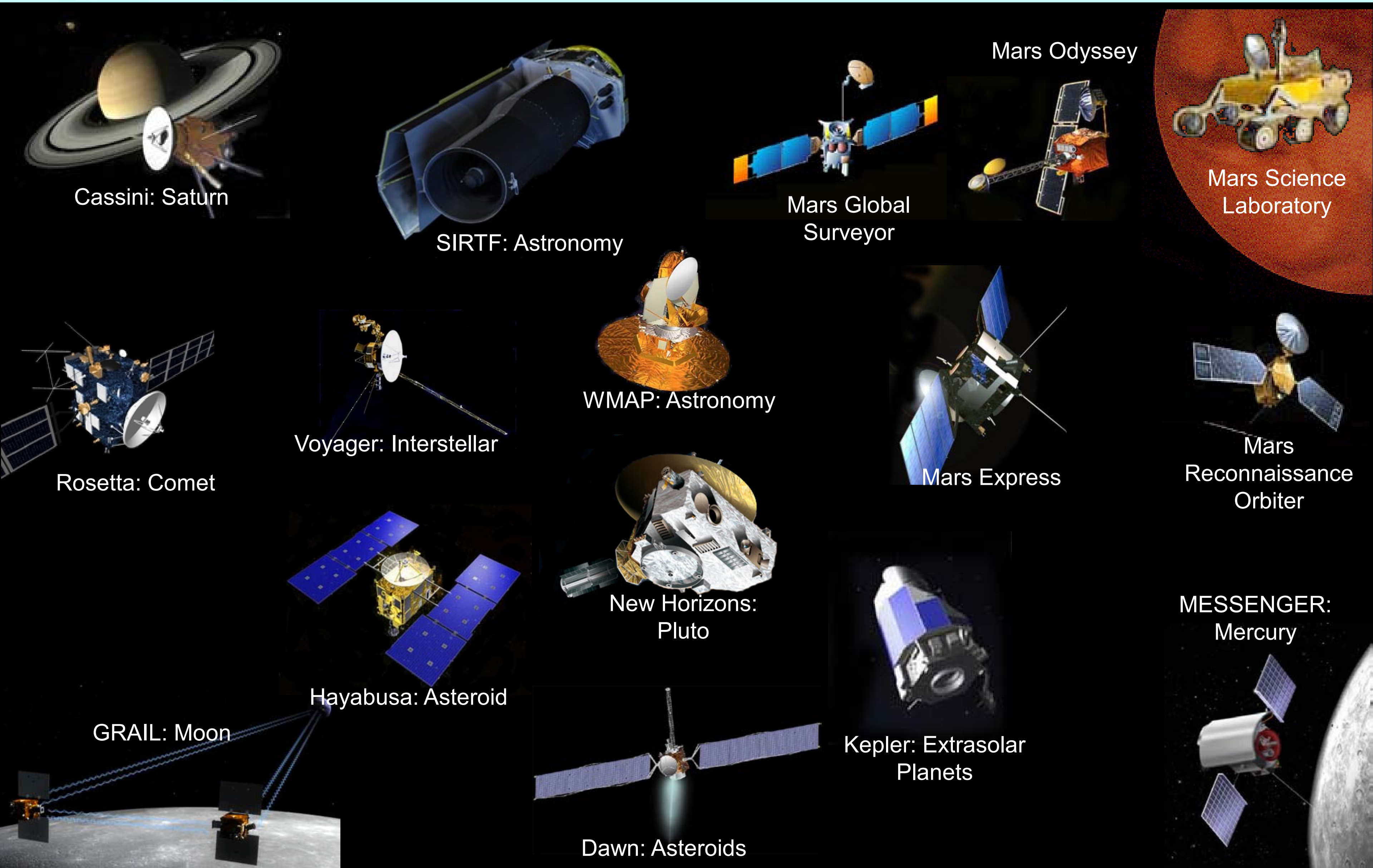
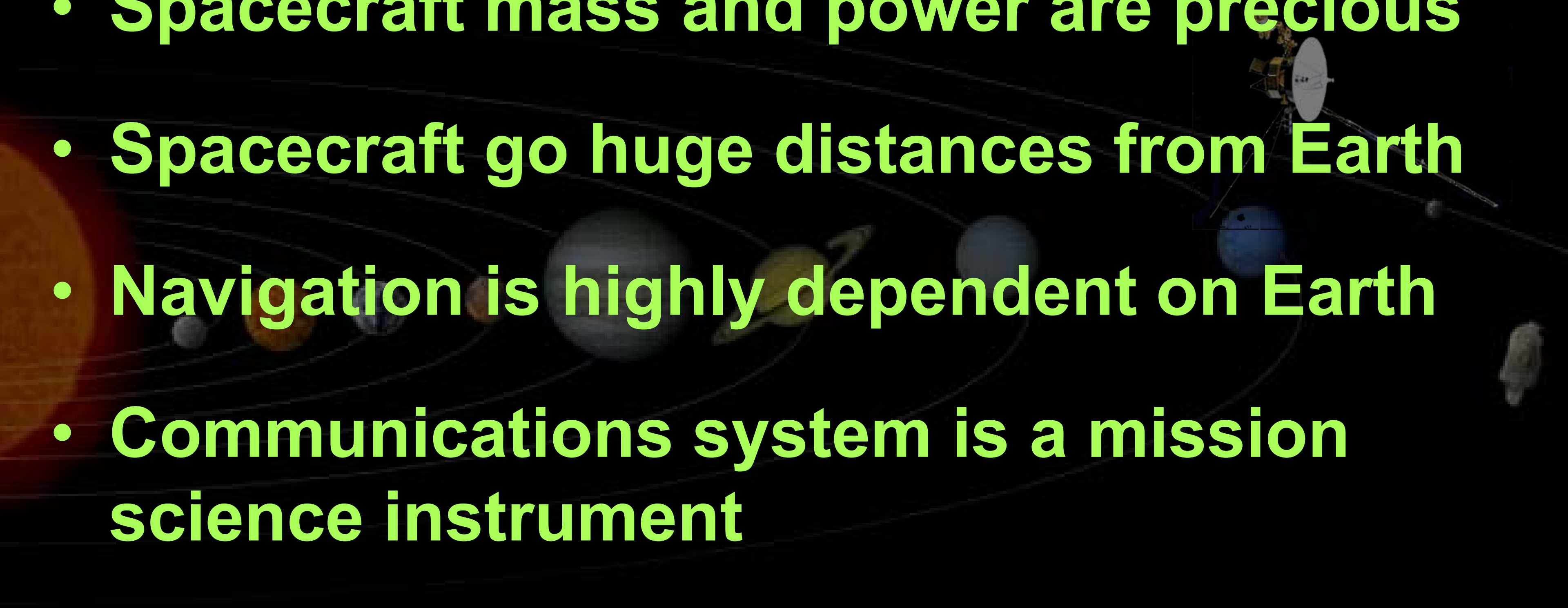
Some Current Deep Space Missions



Deep Space is Unique



- Spacecraft mass and power are precious
- Spacecraft go huge distances from Earth
- Navigation is highly dependent on Earth
- Communications system is a mission science instrument
- Every mission is unique

Space Loss

- **All else being equal, communications performance is inversely proportional to distance squared**

P_T/N_0 = constant / d^2

- **Need to overcome this problem of physics to be successful in deep space**

Why Telecom is Hard

Relative Difficulty

Place	*Distance*	*Difficulty*
Geo	*4×10^4 km*	*Baseline*
Moon	*4×10^5 km*	*100*
Mars	*3×10^8 km*	*5.6×10^7*
Jupiter	*8×10^8 km*	*4.0×10^8*
Pluto	*5×10^9 km*	*1.6×10^{10}*

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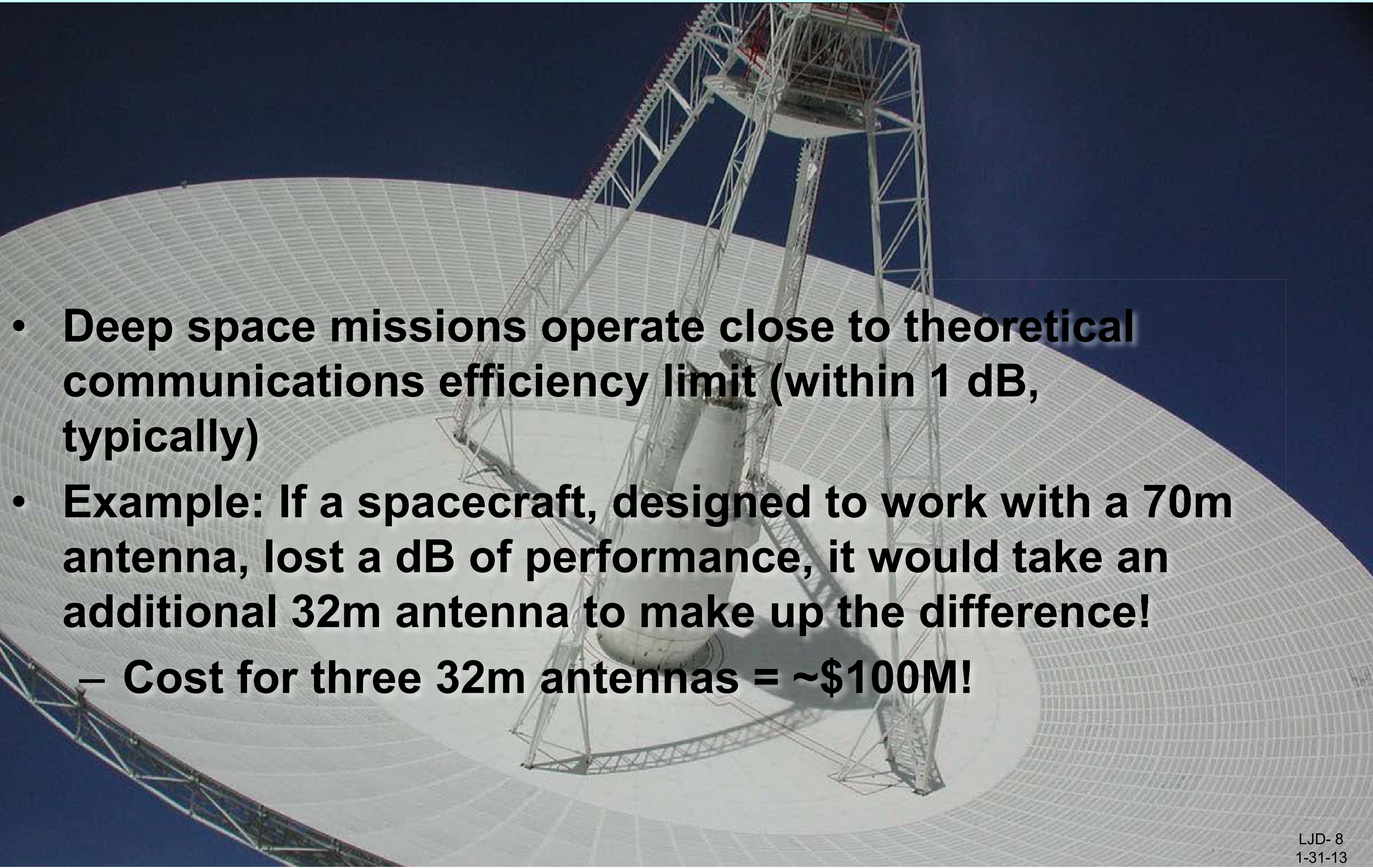
NASA's Deep Space Network

- **Giant (34m and 70m) antennas in three locations around the world**
- **Provides communications with missions beyond GEO**

Spacecraft Mass & Power

- Deep space missions must leave Earth's gravity well – very difficult
  - An Atlas V 551 can lift about 19,000 kg to LEO but only ~500 kg to deep space
- Power generation is very difficult for a spacecraft far from the sun
  - Solar flux goes down by a factor of four each time the distance from the Sun doubles, so a solar panel at Jupiter can only generate a billionth the power as at Earth
  - Nuclear-based generators are both expensive and politically sensitive

Cannot Waste a dB

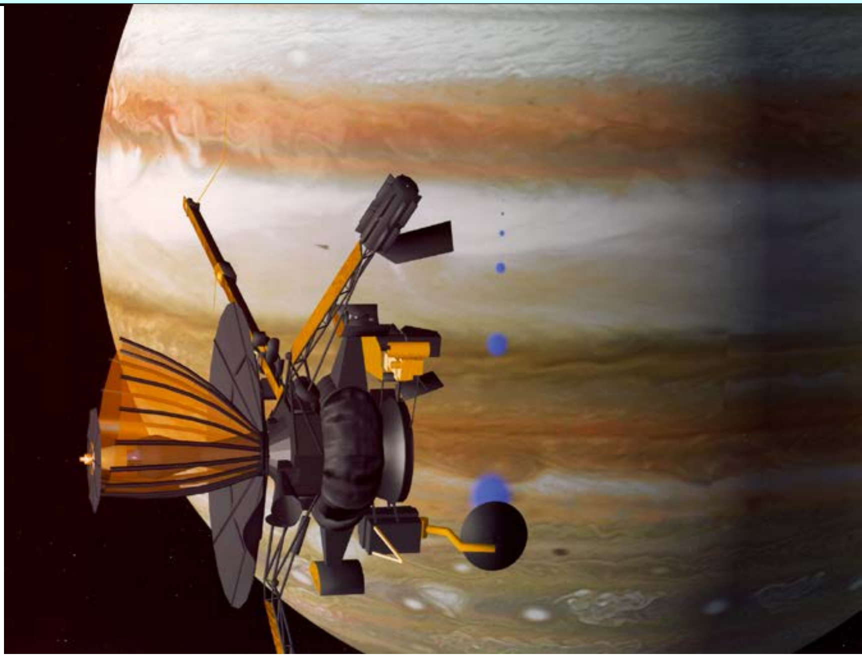


- **Deep space missions operate close to theoretical communications efficiency limit (within 1 dB, typically)**
- **Example: If a spacecraft, designed to work with a 70m antenna, lost a dB of performance, it would take an additional 32m antenna to make up the difference!**
  - **Cost for three 32m antennas = ~$100M!**

Autonomy

- It can take minutes to hours for signals to travel between the spacecraft and Earth
- Decisions must often be made faster than this – requiring spacecraft autonomy
- Spacecraft are usually "sequenced", meaning they are programmed to operate for long periods without commands from Earth
- Spacecraft manage the data they acquire, storing it until it can be sent back to Earth
- Emergencies require special "safing" algorithms

Case Study 1
Galileo Mission to Jupiter

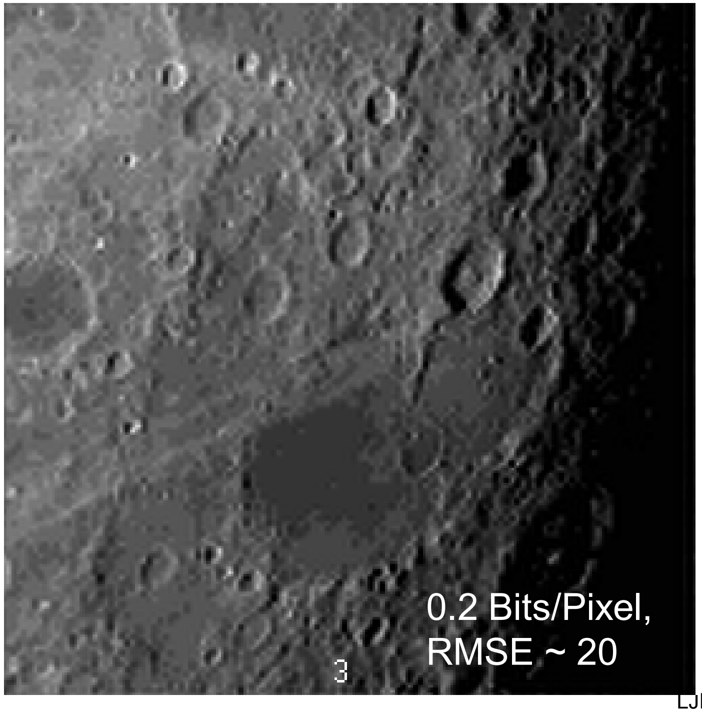


- NASA flagship mission launched in October 1989
  - Delayed several years by Challenger accident
  - Radioisotope generators already partially depleted
- High gain antenna (HGA) failed to deploy
- Left the comm system with 10^{-4} disadvantage
  - Hemispherical antenna instead of HGA
  - S-band instead of X-band
- Spacecraft was fully functional except for the HGA
- Lucky break
  - Twice as much RAM onboard as in the original design

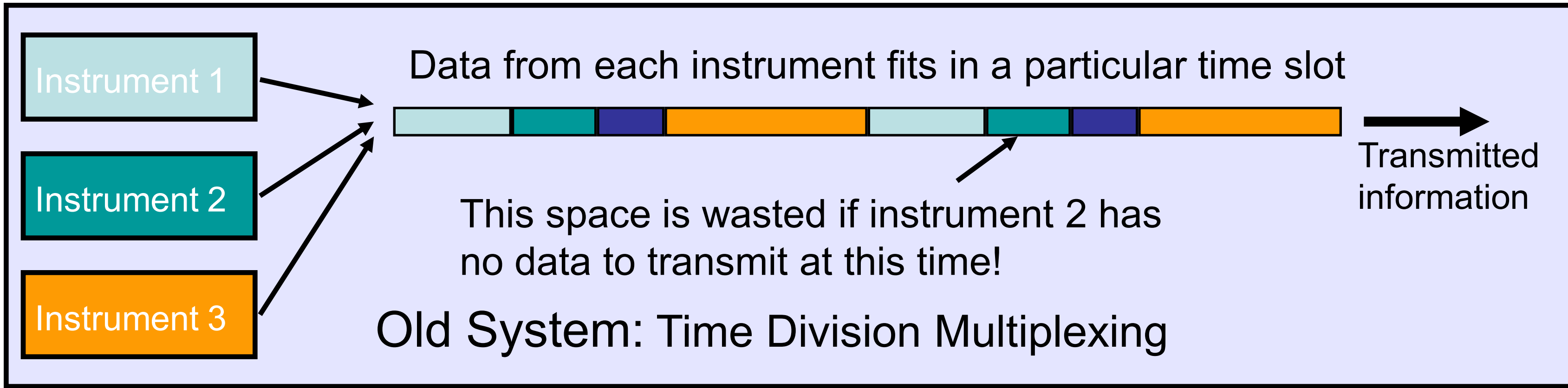
Cmpresion 4 GLL

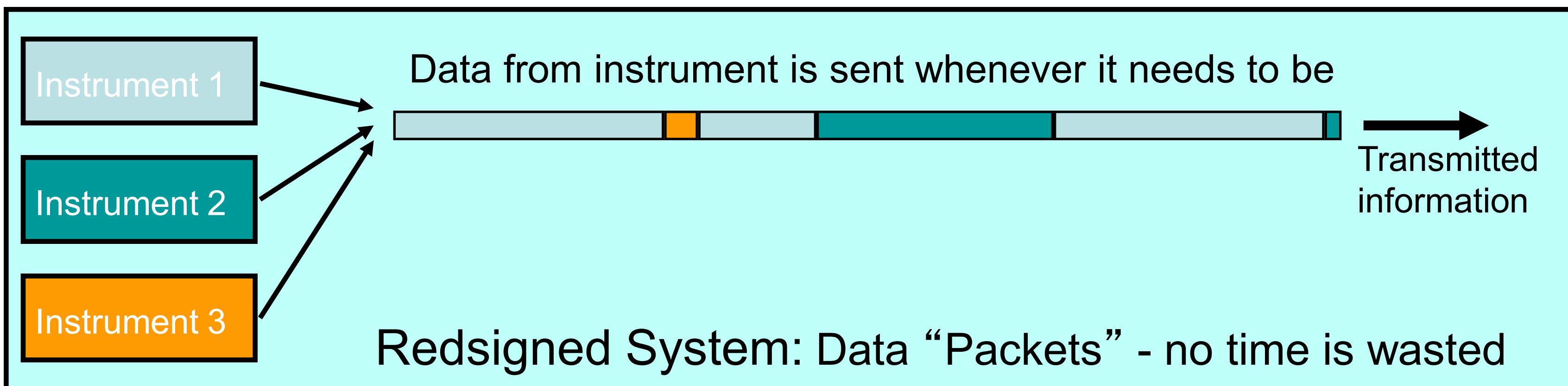
- Before Galileo, deep space missions used "lossless" compression
  - Low compression ratios - typically no better than 2:1
  - Well understood, deterministic errors, caused mainly by data overflow
- We added Integer Cosine Transform algorithm – similar to JPEG
  - Compression ratios could be set – typically between 5:1 and 20:1
  - New error containment strategies made this viable for deep space
  - Error artifacts are better understood due to research in support of Galileo
- Galileo was forced to determine which information is most important from each instrument and subsystem – data editing

All subsequent deep space missions have used compression and editing



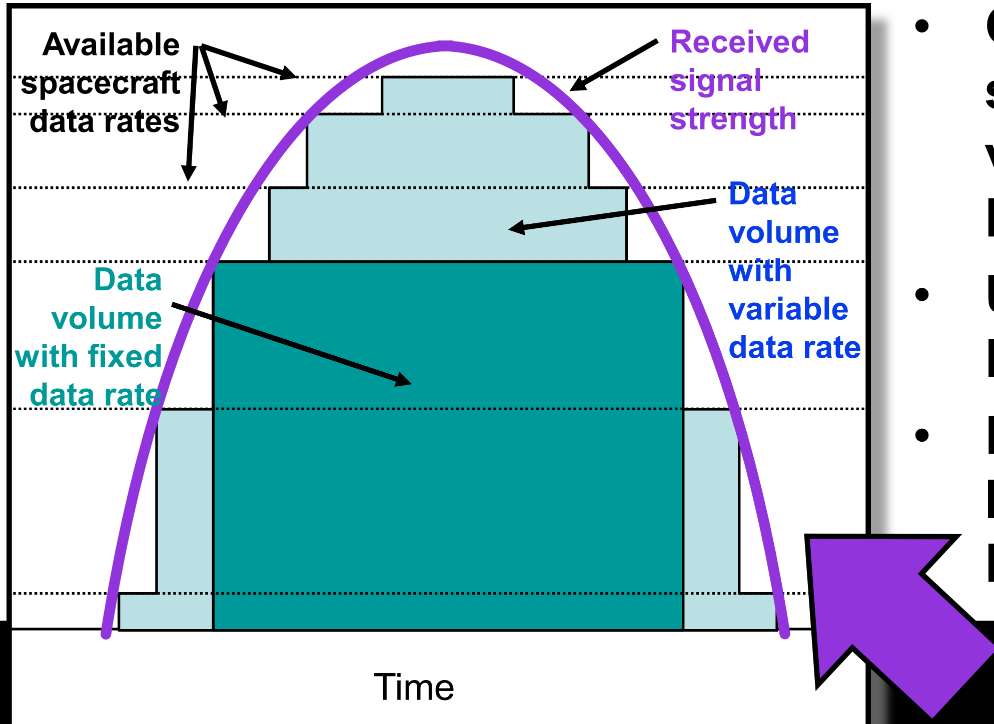
Packetized Telemetry

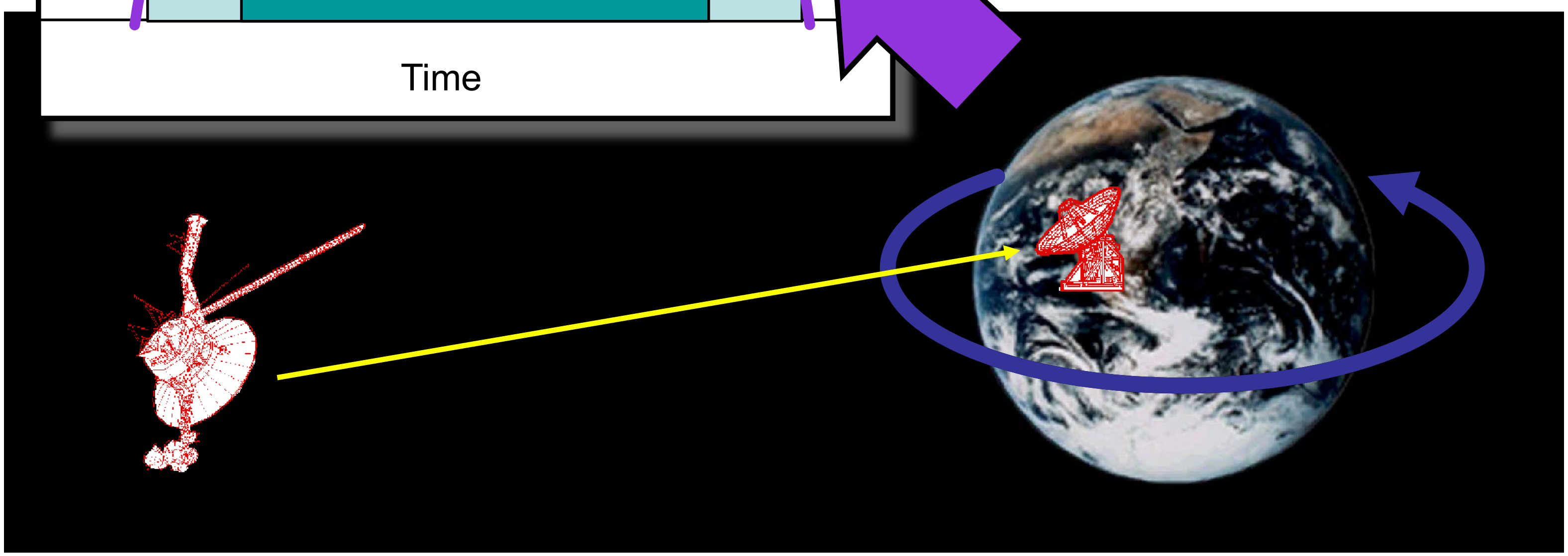




- **All subsequent deep space missions use packet telemetry to eliminate wasted space in the transmitted information**

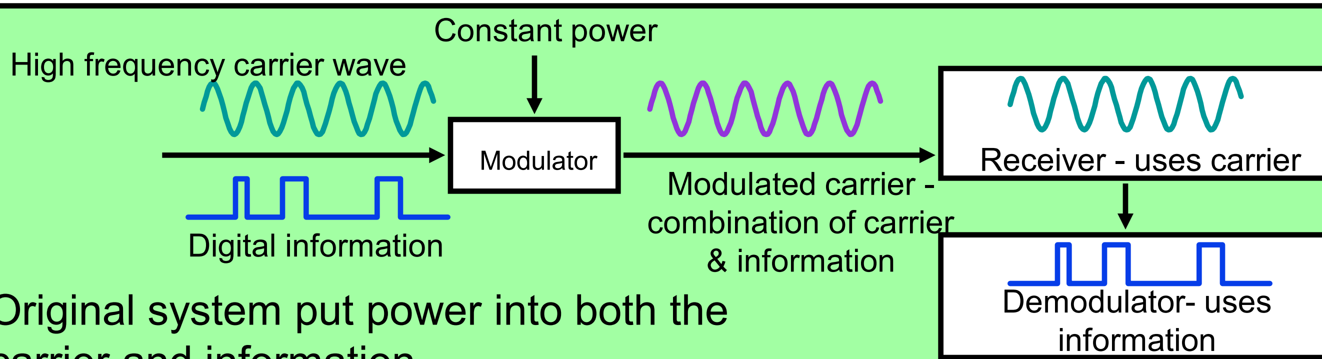
Variable data rates



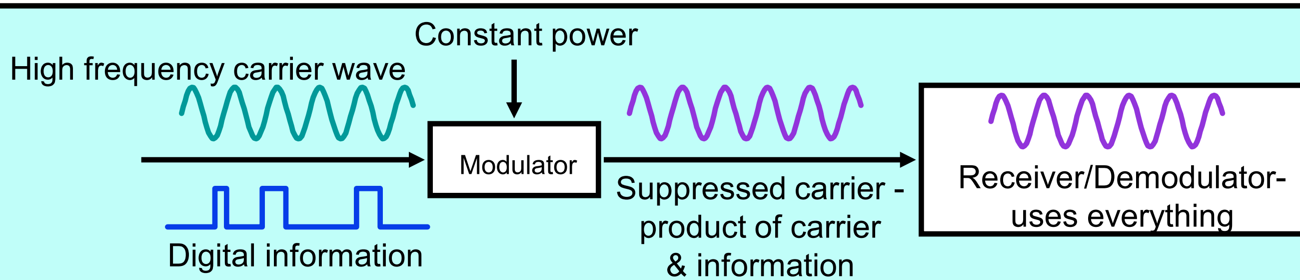


- Galileo was the first deep space mission to use variable data rates during DSN passes
- Used prediction of signal levels
- Led to investigation of Internet-like protocols – DTN

Modulation



Original system put power into both the carrier and information

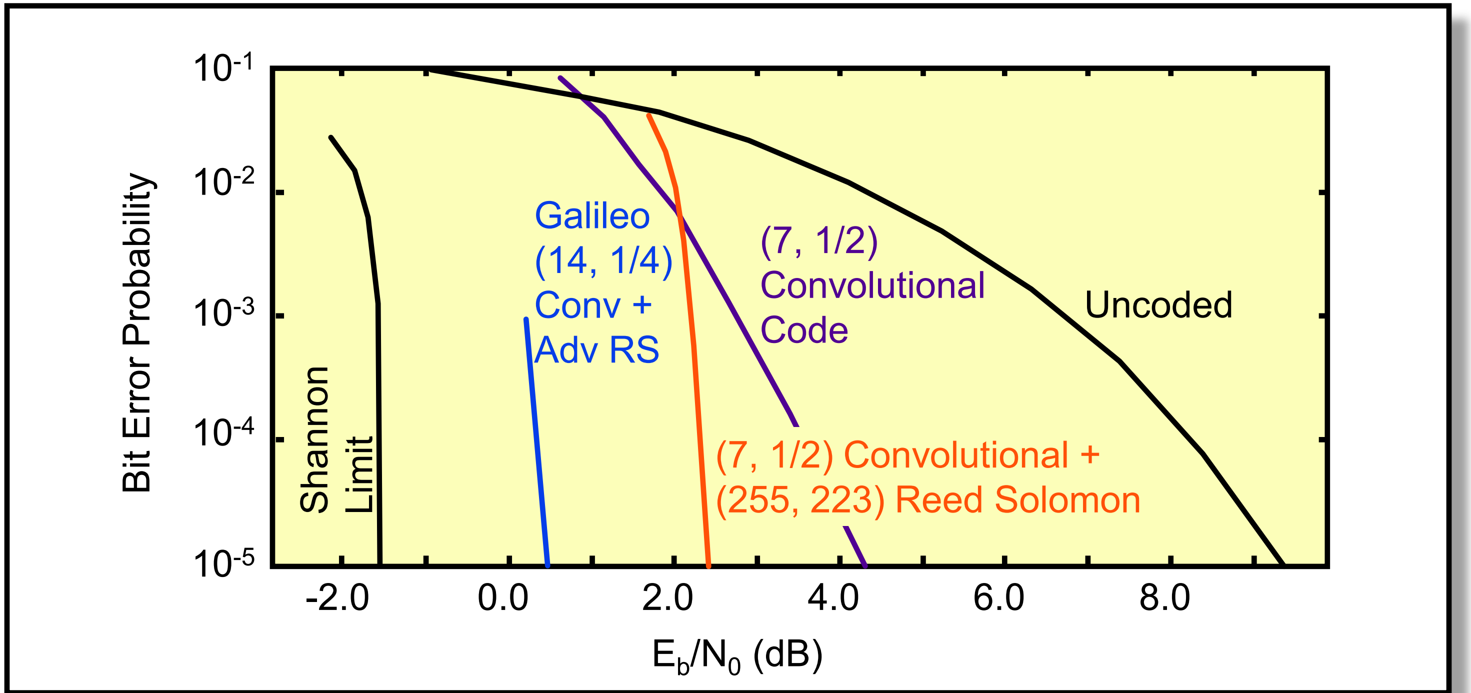


The redone Galileo system put all the available power into the information stream. This was enabled by a new generation of DSN receivers that could demodulate this format at very low signal levels

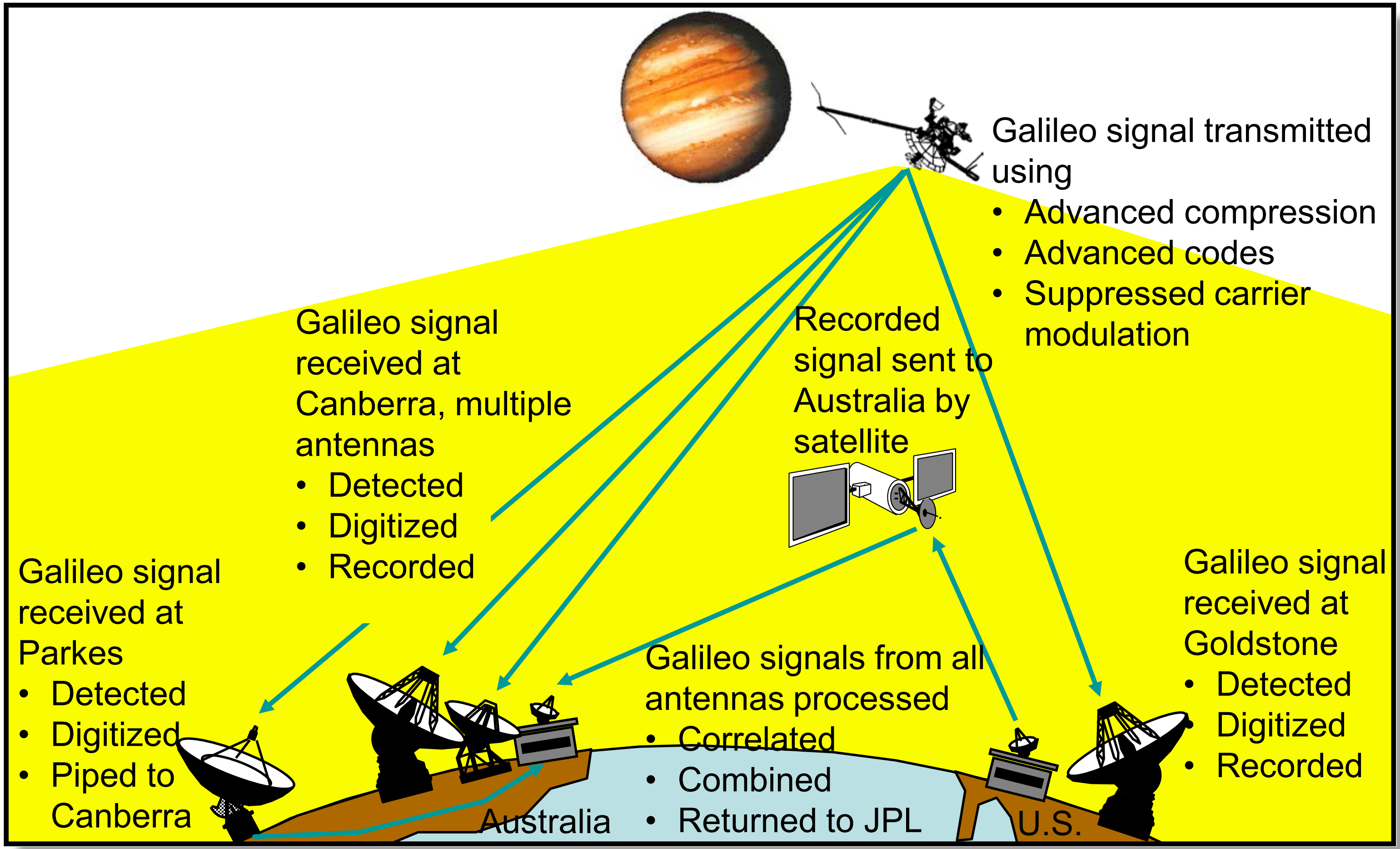
- **Suppressed carrier modulation is now available to all future deep space missions**

Errer-correcteng kodes

- Error correcting codes had been used for many years in deep space
- Galileo's redesigned codes were the best yet flown
- Among the new coding techniques on Galileo were variable redundancy, and redecoding – applicable to future codes as well
- Subsequent missions leverage these techniques and continue to evolve better codes

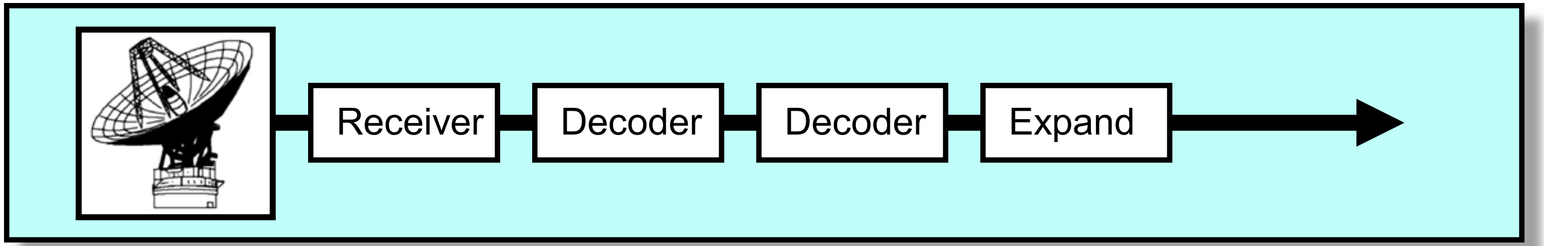


Antenna+Antenna+Antenna... Arraying

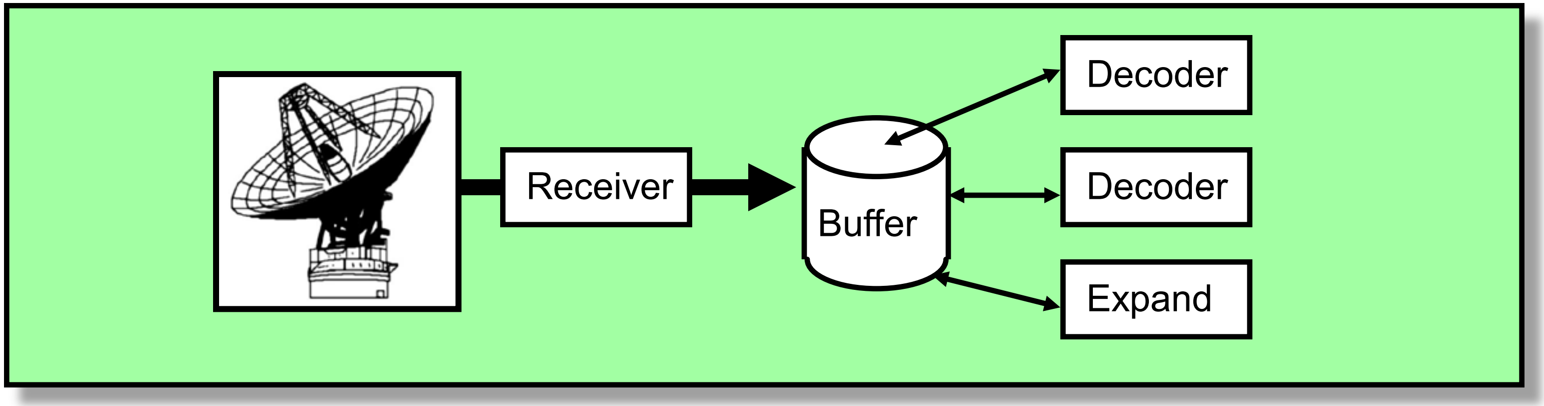


- **The DSN now routinely supports arrays – but only within the DSN**
- **Arrays are be used for special mission events and to synthesize 70m antenna performance from smaller antennas – serving as backups for the 70m antennas**

Asynchronous processing

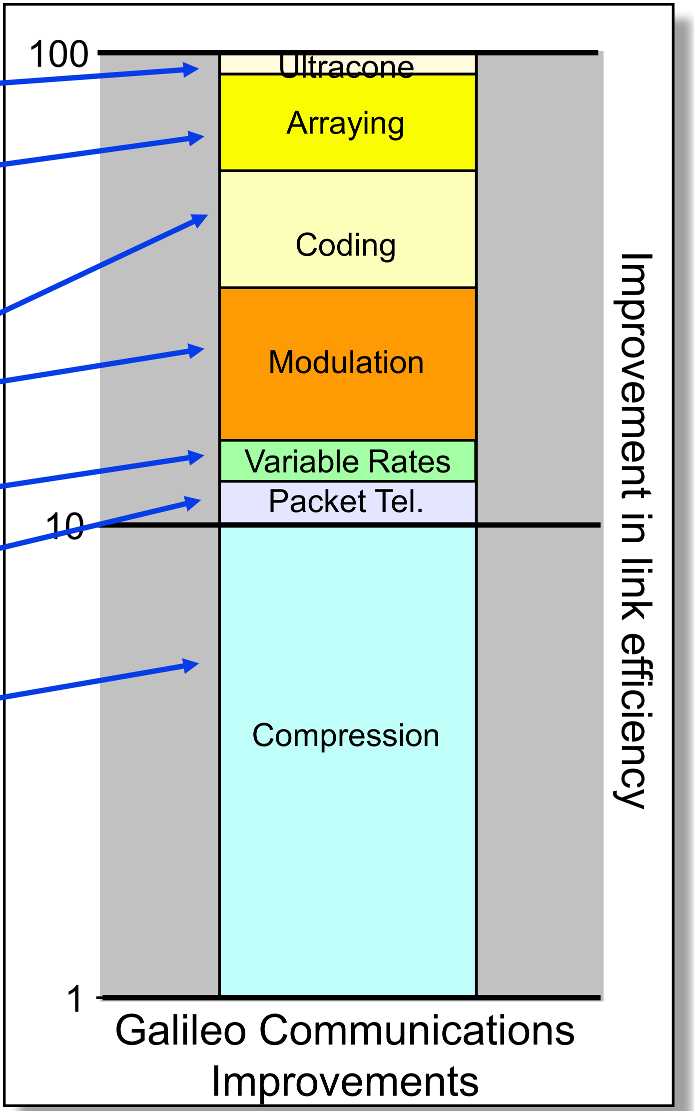


- For Galileo, all DSN processing after bit detection was performed on demand
- This system is more modular, efficient, and cheaper to maintain than the old serial system
- Although this does not increase link efficiency, the DSN is evolving to this architecture – a lower-cost legacy for all future missions



Summary of Galileo repairs

- **Optimized Signal Detector**
- **Antenna arraying**
- **Advanced error-correcting codes**
- **Efficient modulation**
- **Variable data rates**
- **Packet telemetry**
- **Data compression**

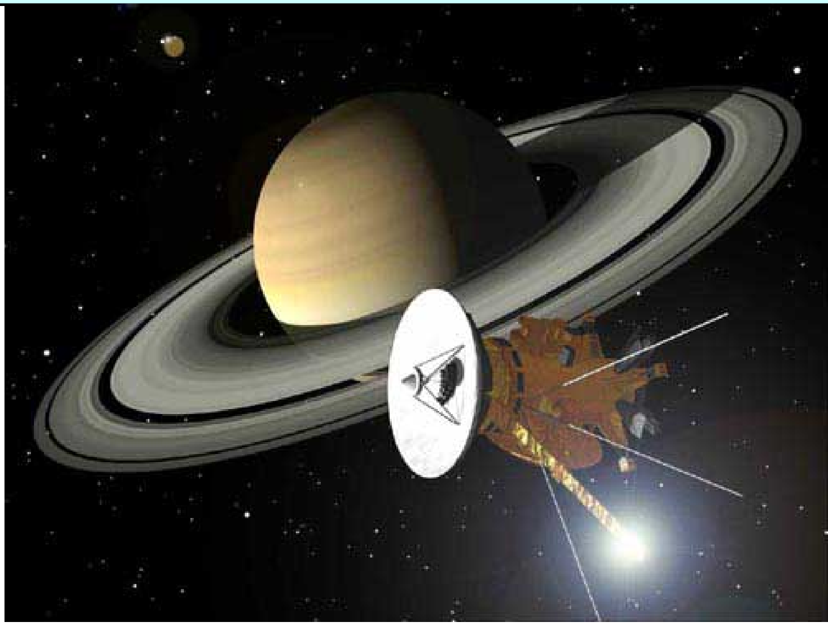


Galileo – Conclusion

- Galileo was able to increase its effective data rate from less than 10 bps to around 1 kbps
- The mission was a complete success, achieving more than 75% of its original science goals during the 2-year prime mission
- Galileo went into extended mission and was eventually crashed (intentionally) into Jupiter to avoid possible contamination of the moons
- All of the communications improvements that were made to Galileo became standard on subsequent missions
- Additional “lesson learned”: It is good to have reprogrammability on a deep space mission

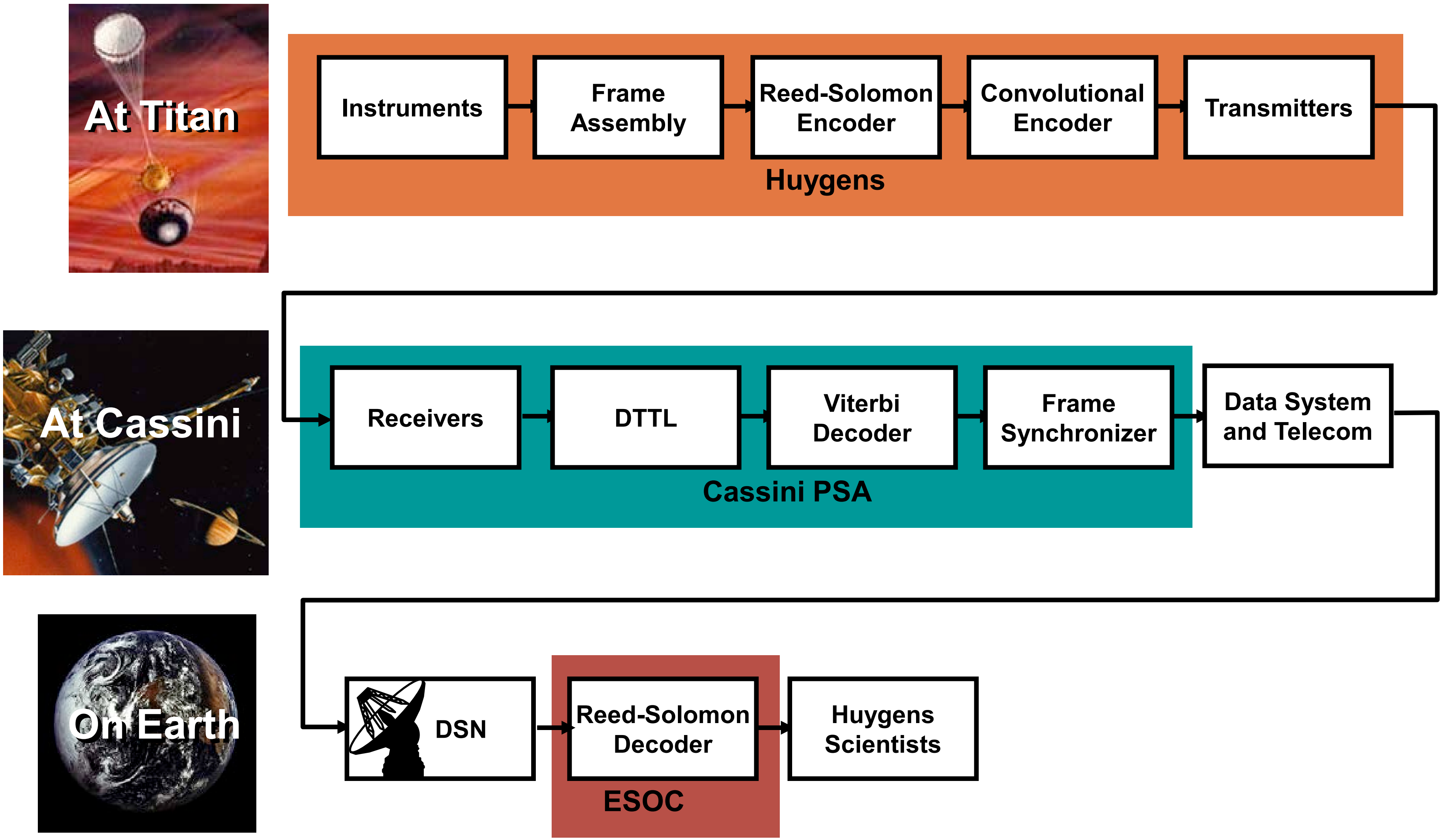
Case Study 2

Cassini/Huygens Mission to Saturn



- **Launched in July 2004**
- **Cassini was the NASA flagship mission to Saturn, Huygens was an ESA-built daughter probe for exploring Titan**
  - **Huygens would descend into the atmosphere to Titan and use Cassini to relay signals to Earth**
- **Everything looked great during Cassini/Huygens cruise to Saturn**
- **A very clever test of Cassini relay radio, using the DSN to mimic Huygens, showed that Huygens was going to fail**

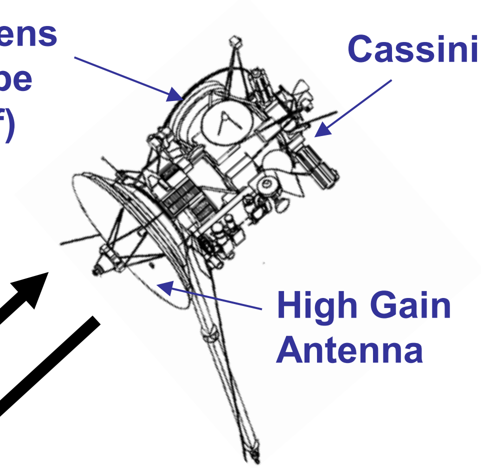
Huygens Telecommunications System



Discovering the Problem

Huygens Probe (off)

Cassini



High Gain Antenna

S-band (2 GHz) radio signal transmission from Goldstone simulating Huygens Probe transmission (one-way light time was ~ 40 min)

X-band (8 GHz) Cassini telemetry

Huygens Test Equipment

JPL

ESOC

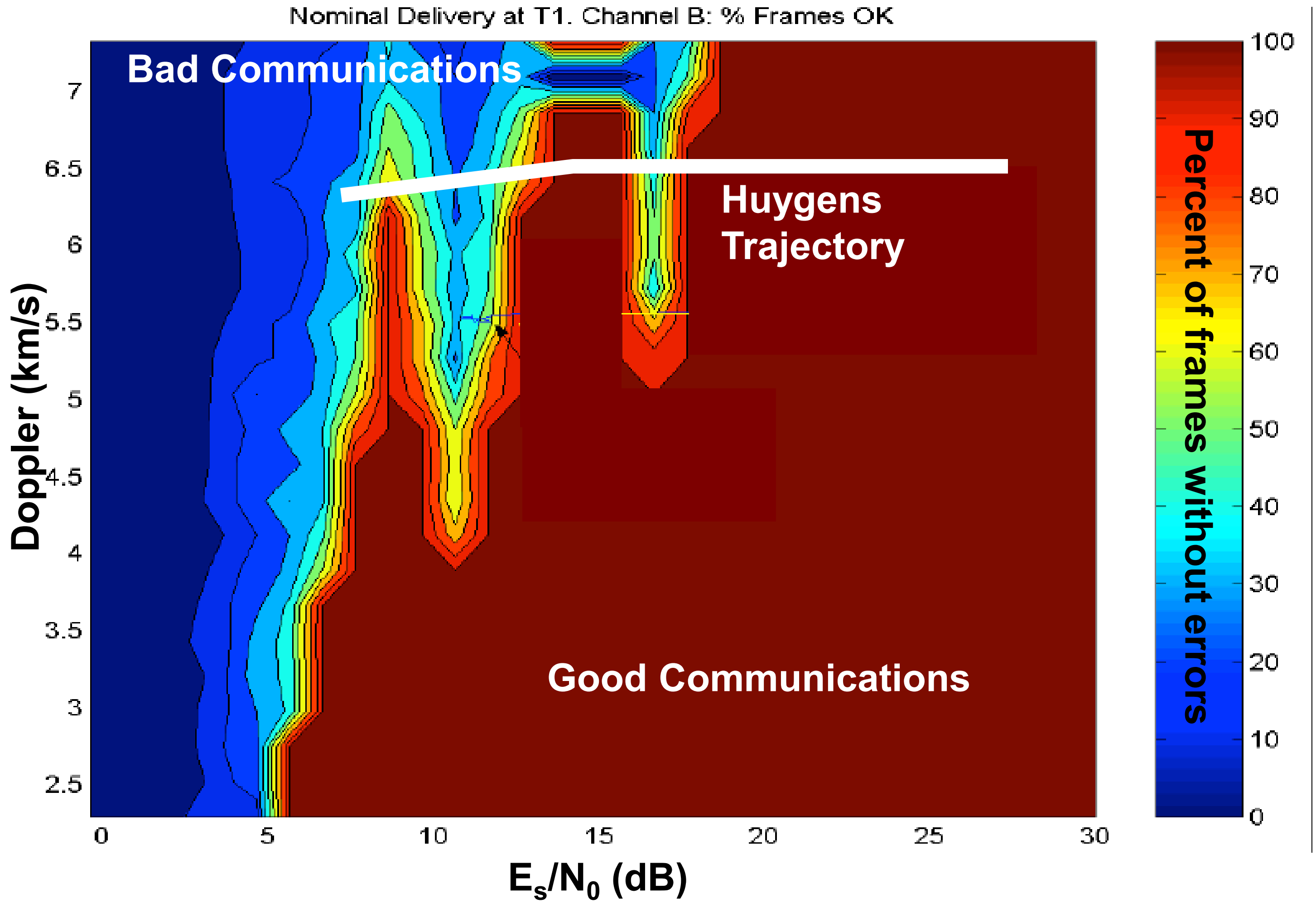
DSS 24
Deep Space Network Antenna

Data Evaluation

Data arrive at ESOC 80 min after transmission From Goldstone!

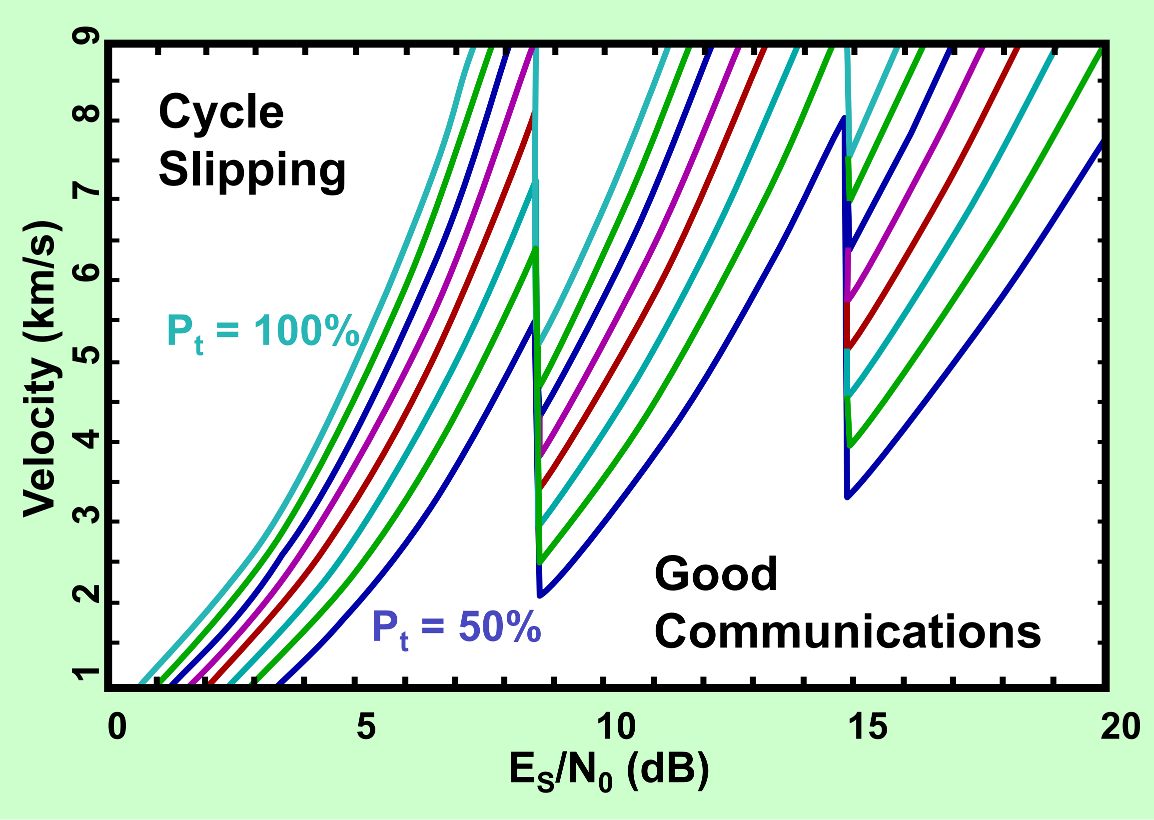
Boris Smeds and Test Equipment

Test Results



Modeling the Failure Mechanism

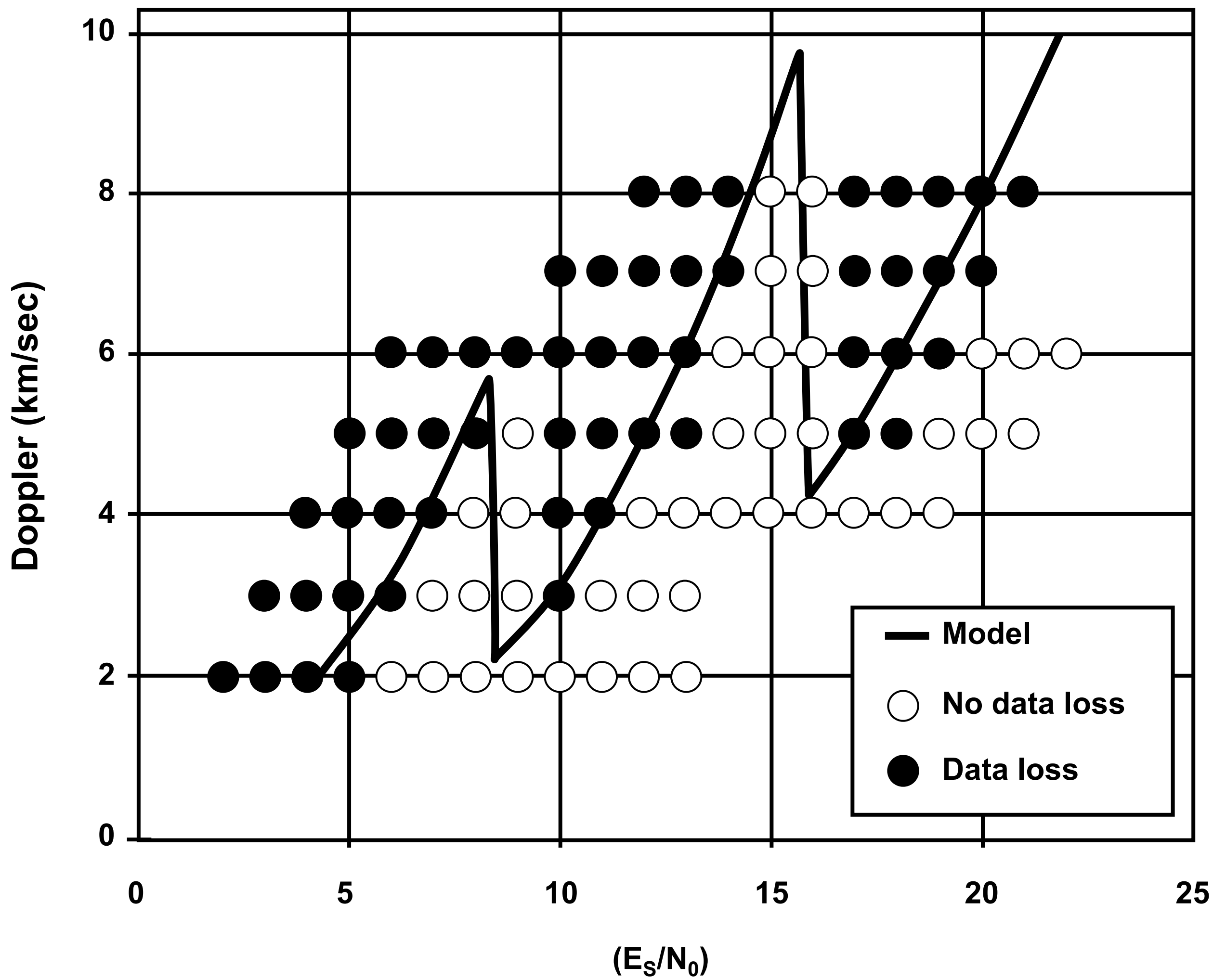
- A complete model of the relay system was developed including
  - Symbol loop dynamics as a function of bit transition probability
  - Coding and synchronization
- Symbol cycle slips were generated with a period that is a function of E_b/N_0, Df, and P_t
- Fingers turned out to be caused by AGC function
- Analysis showed the anomaly was caused by symbol loop bandwidths
- Unfortunately, these parameters were hard-coded and could not be changed in flight



- The Galileo "lesson learned" was not learned well enough

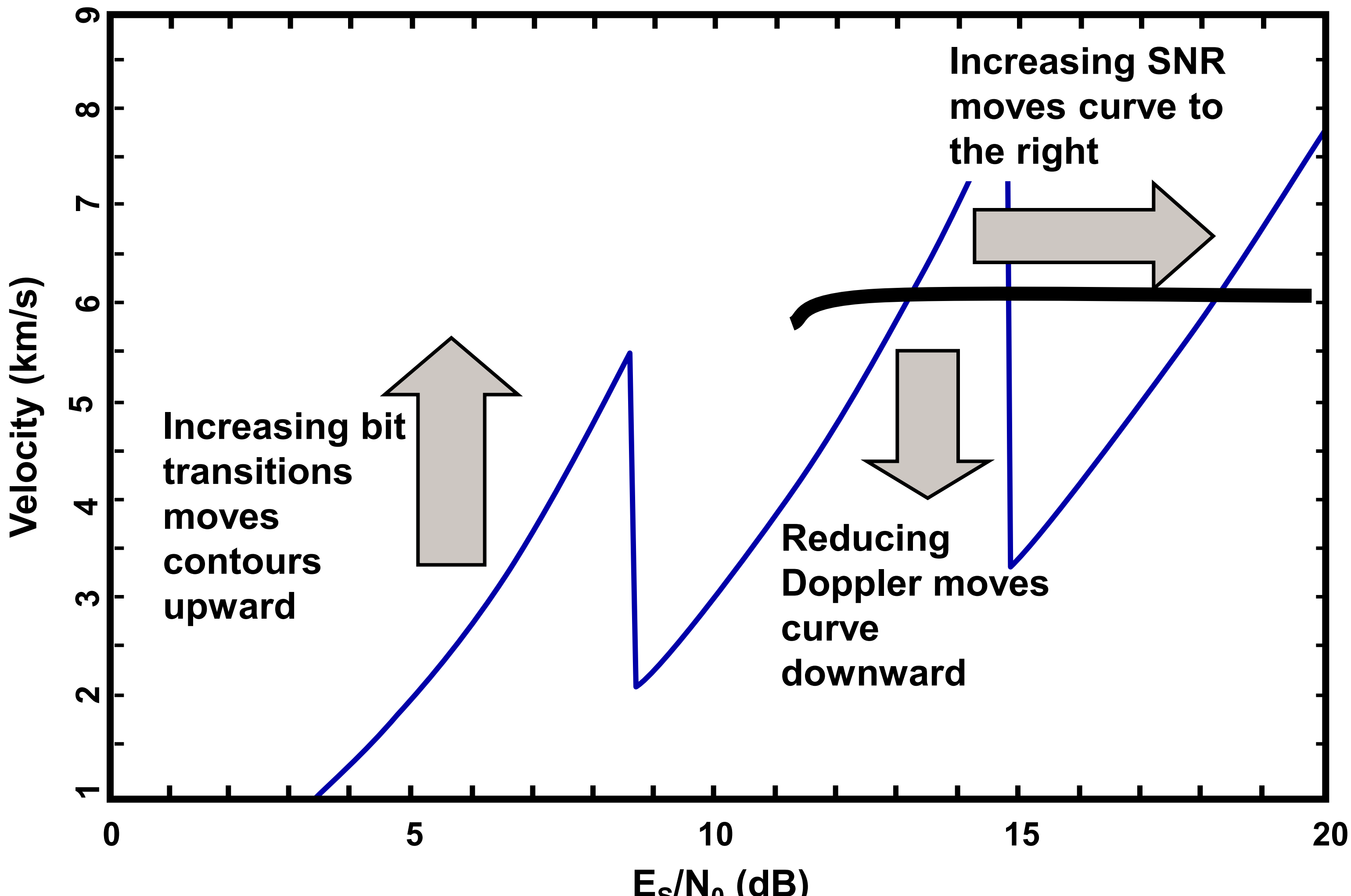
Verifying the Model

- **Additional DSN tests were run to verify and calibrate the model**
- **Results were excellent**



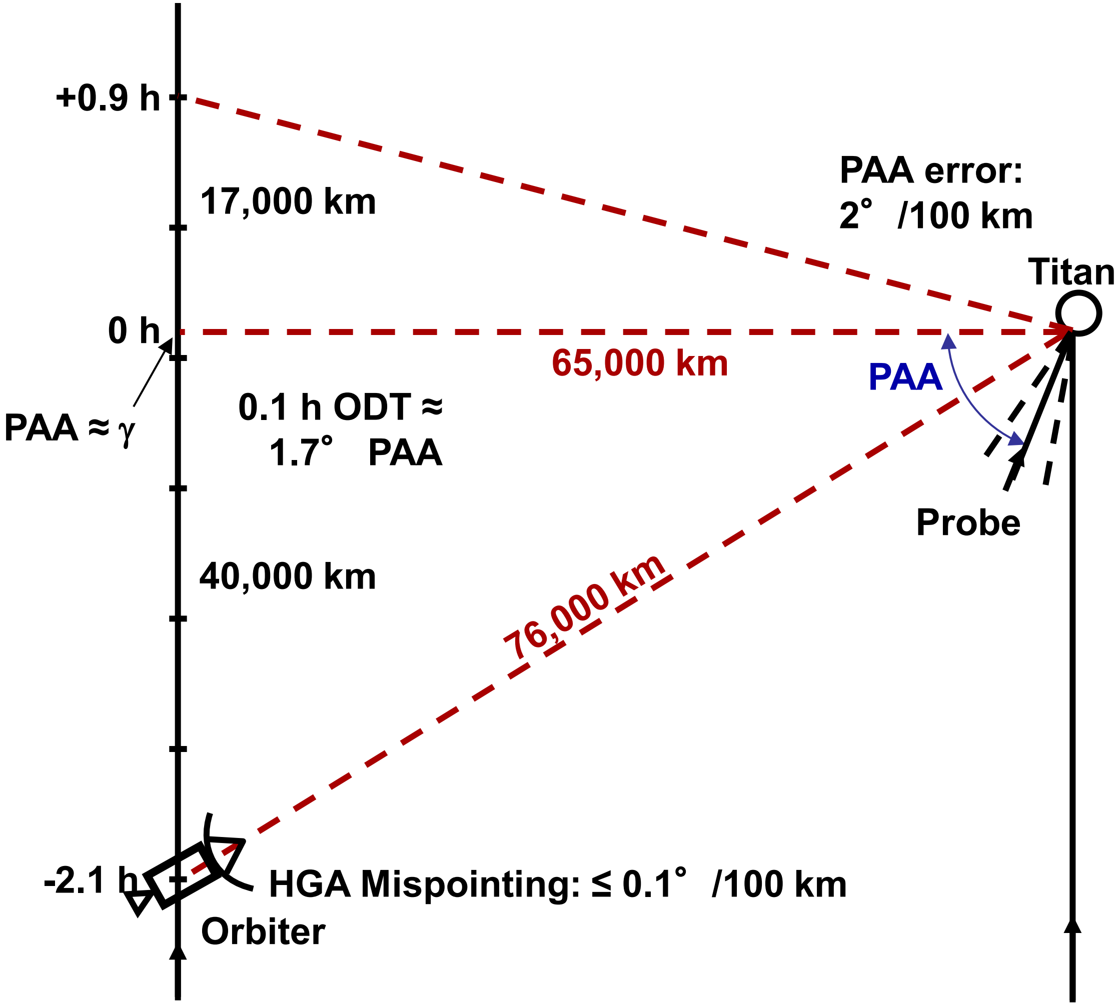
Ways to Improve Data Return

Varying the critical parameters "moves" the probe curve with respect to the contours - resulting in more good data returned to Earth



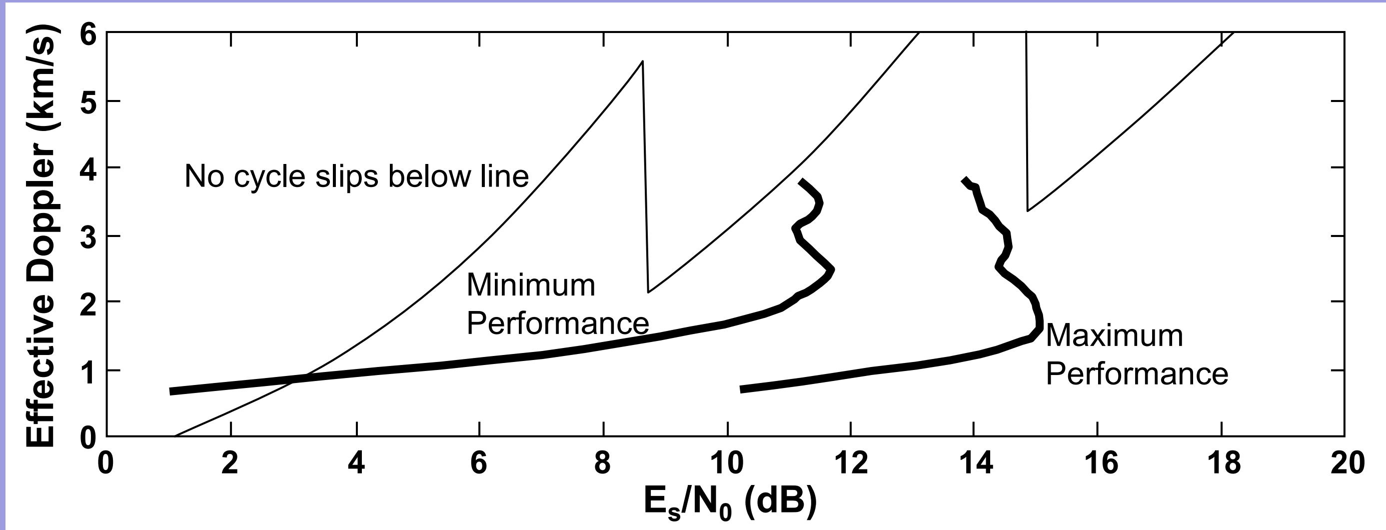
A New Retrograde Flyby Saves the Day

- The trick now was to find a high altitude flyby that uses minimal fuel (~150 m/s for simple altitude increase)
- JPL navigators came up with the idea of flying by the opposite side (retrograde) of Titan
- This uses Titan's gravity to help more with Cassini maneuvers
- New trajectory minimized additional propellant needs (~100 m/s)
- There is actually a class of these trajectories with one ultimately chosen by the Project



Recommended Solution

- The team developed several point designs that showed possible solutions to the anomaly
  - Each of these would return close to 100% of the data with margin
- The trick here was that communication performance had to be bounded both from above and below
  - Too much margin is bad!
- Our experience with Galileo (operating 0.5 dB from theoretical) helped



Probe Data Playback

- **Cassini turned its HGA to receive probe data during actual descent**
  - **No visibility during actual probe mission was possible**
- **After turning to Earth, Cassini commenced playing the probe data to the DSN**
  - **Eight full copies were sent, over all DSN complexes**
  - **Provided redundancy for the data playback**
  - **Provided resiliency in case of any two 70m failures**
- **One of the two communications channels on Huygens failed (no data)**
  - **Likely caused by operator error in commanding**
  - **This was a known risk (this is why there were two channels!)**
  - **All housekeeping data was redundant on the two channels**
  - **Most scientists planned their data campaign to satisfy their main goals with either single channel**

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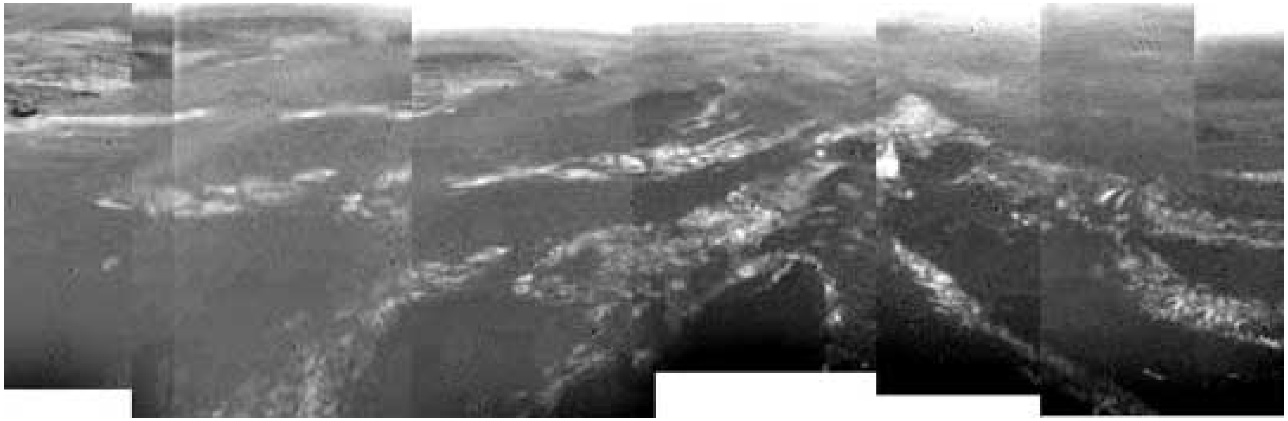
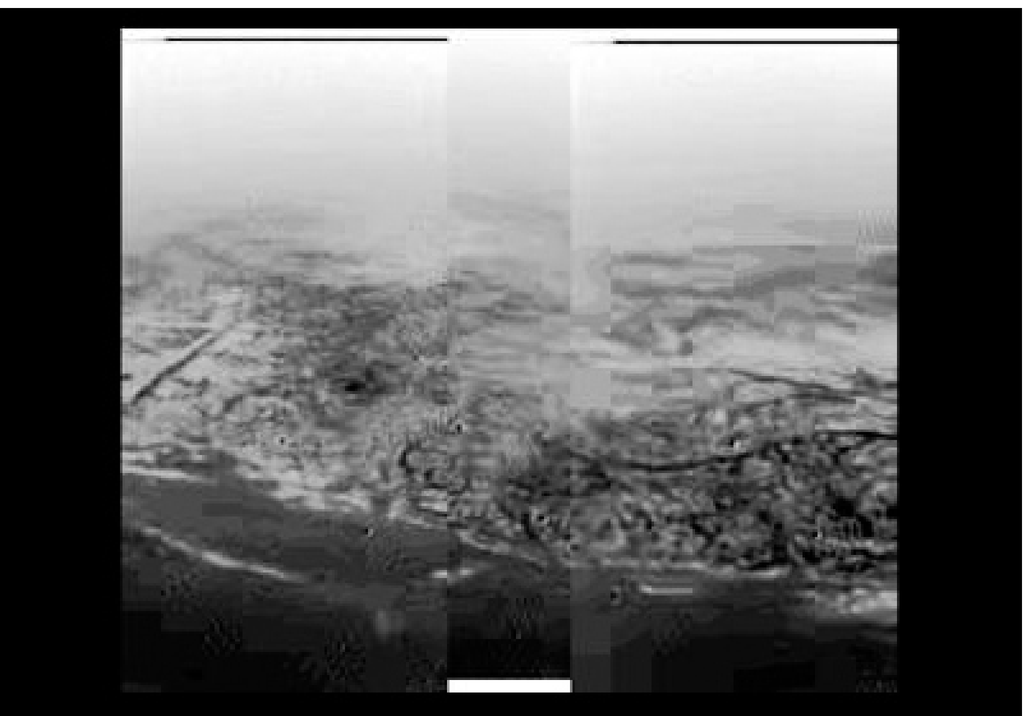
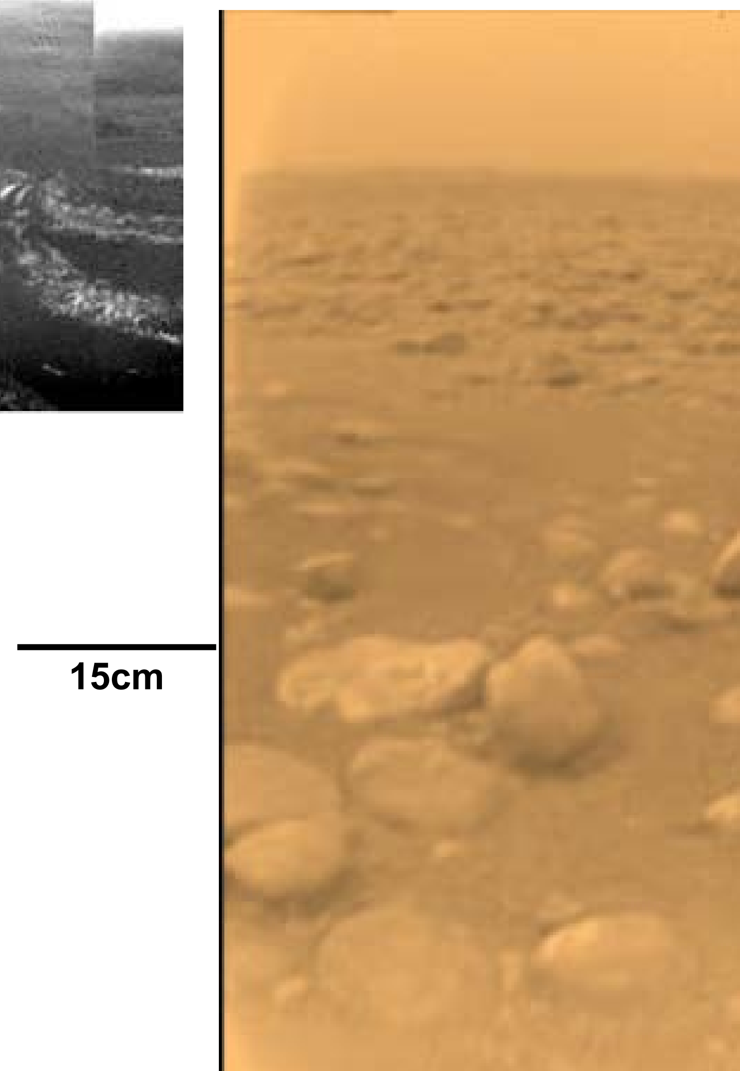
In the End: Success!

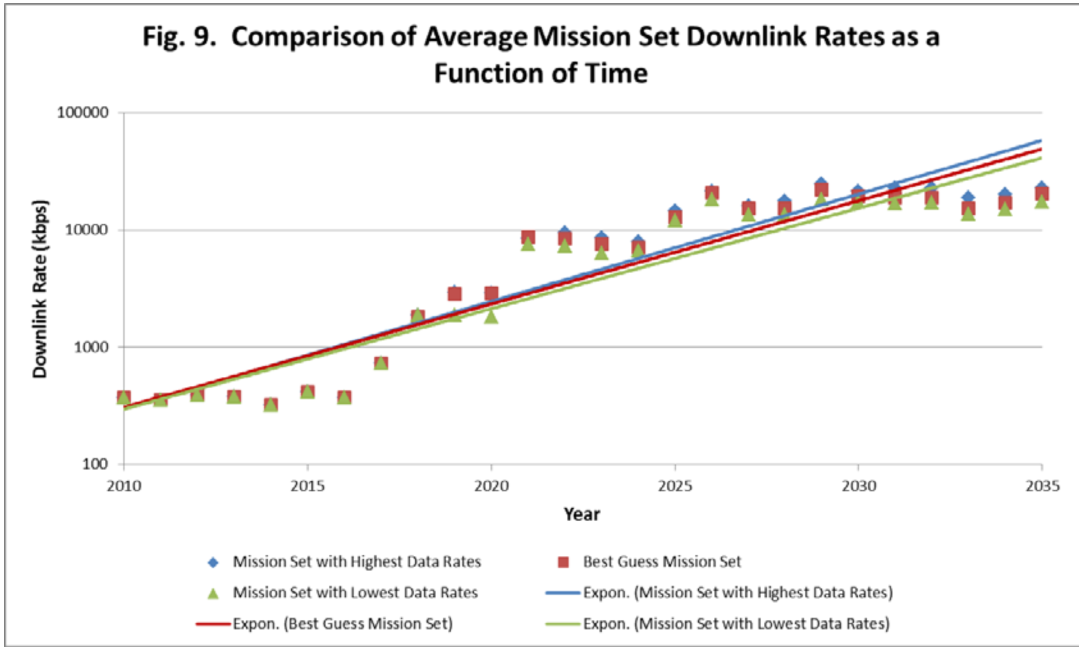






Future Trends

- **Deep space missions are limited by the communications link**
  - **Mars Reconnaissance Orbiter has only mapped 1% of Mars at high resolution**
- **Things will only get worse as missions carry more data-hungry instruments**
  - **Radars, multispectral and hyperspectral imagers**
- **When humans go into deep space, they will need much higher bandwidth comm**



Emerging Technologies

- Among the technologies that will likely come into play:
  - Software defined radios
  - High frequency radio communications (e.g. 32 GHz and above)
  - Optical communications
  - More advanced data compression
  - More onboard intelligence and autonomy
  - Space internetworking
  - Quantum communication and sensing

What Keeps Me Awake Today?

- **Deciding which emerging technologies to pursue**
  - Finite funding and finite researchers mean we have to place our bets carefully
- **Ensuring we have future researchers**
  - We see fewer students pursuing communications today
- **Making sure missions use the new technology**
  - Missions are, by nature, risk averse
  - We need new processes that make it easier to infuse these technologies

Conclusion

- There are real problems to be solved in deep space communications
- Most often, smart solutions lead to new kinds of space missions
- Sometimes, smart solutions save spacecraft that are in jeopardy
- The space business needs a next generation of smart problem solvers