

# Galileo's Communications Legacy to Subsequent Deep Space Missions

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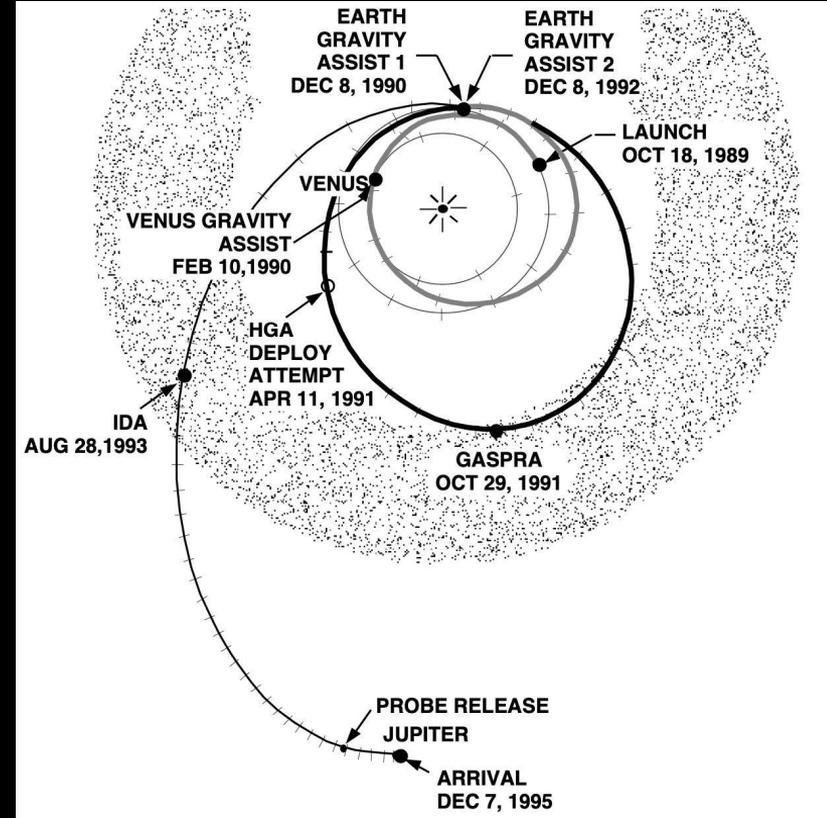
# Who Am I?

- I was a Caltech student starting in 1972
  - BS, MS, PhD in Mathematics
- Caltech Organist since 1974
- At JPL from 1980 until 2022
  - Research in communications
  - Managed the Communication Research Section
  - Managed the DSN Advanced Systems Program
  - Retired as Deputy Director for Interplanetary Networks
- Career intersected with Galileo for a short but critical period

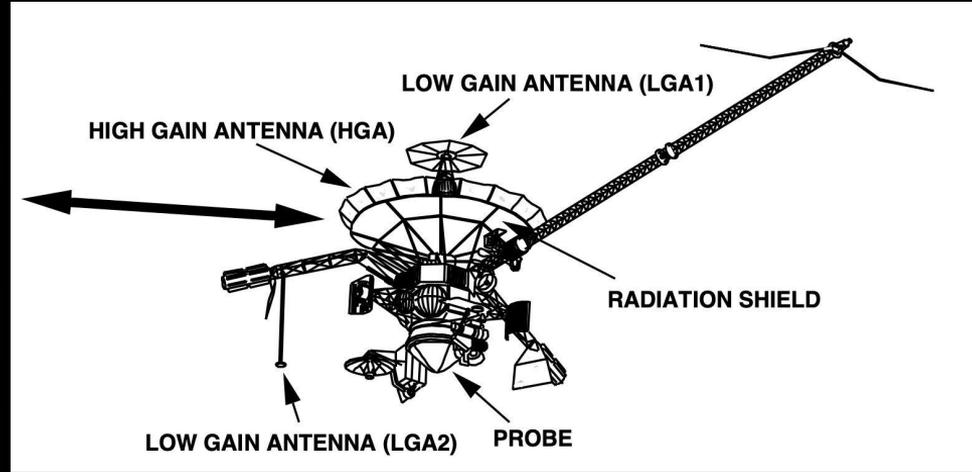


# Changes in the Galileo Mission Trajectory

- Delay in the Shuttle Program resulted in a longer, more complex Galileo trajectory
- Less power at Jupiter because of the additional decay of radioactive material
  - My program had designed a more complex communications encoder that was installed on Galileo to compensate for this
- New trajectory had 1 Venus and 2 Earth flybys
- Radiation shield added behind High Gain Antenna (HGA) for Venus operations
- HGA could be deployed only after Galileo returned toward Earth from Venus
- When it did, the HGA only partially opened



# Using the LGA System Instead of the HGA



- Galileo continued to operate using its two small Low Gain Antennas (LGA's)
- The LGA's were only capable of transmitting at S-band (2.3 GHz) instead of the higher X-band (8.4 GHz) possible with the HGA
- The combination of the frequency and gain differences resulted in a factor of 10,000 (40 dB) disadvantage

# Spacecraft Health and Prognosis after Flybys



Galileo photo of the Asteroid *Gaspra*

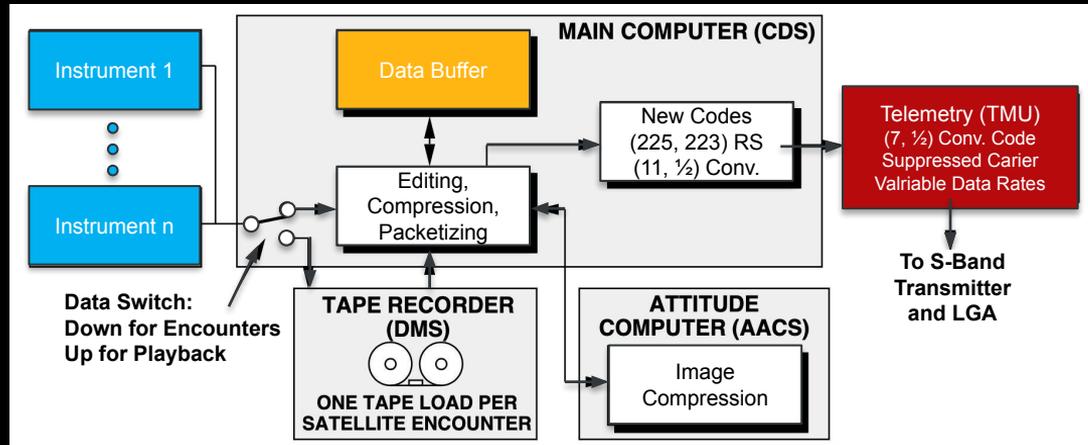
- Galileo was otherwise completely healthy
- Both Earth encounters and one with Gaspra were accomplished using S-band and the LGA's
- The problem: As Galileo got closer to Jupiter (hence farther from Earth), the data rate would become unreasonably low
- If we did not make any changes, less than 5 bps would be returned from Jupiter!

# The Galileo S-Band Studies

- My office was already working on solutions to Galileo's problem when JPL's Flight Projects Office officially asked for ideas in the summer of 1991
  - We had conducted a 30-day study using technologists and spacecraft systems people from various discipline areas
- We concluded a good Juptier Orbital Mission was possible with the LGA's
- Based on this, we teamed with the Flight Projects Office on a 90-day detailed study to produce a point design for the entire system,
  - Co-led by Jim Marr from Flight Projects
  - New software would be added to the spacecraft
  - Several new ground enhancements would be added to the Deep Space Network
- The design was presented to two parts of NASA HQ and accepted for implementation in April, 1992

# Solution: Galileo S-band Spacecraft System

White boxes indicate new functions



- At each moon encounter, the tape was filled with data
- Between encounters, the tape data was sent back to Earth
- Simultaneously, low rate science and engineering data were merged into the stream
- Advanced data compression was applied to all data
- Advanced error correcting coding was implemented
- Modulation is fully suppressed carrier for maximum efficiency
- Transmitted data rate was varied to optimize data return

# Communications Link Improvements

- Arrayed several ground antennas together to approximate the performance of one giant antenna with the combined area of the parts
- Installed an optimized S-Band signal detector at the Deep Space Networks largest Australian antenna
- Used suppressed carrier modulation for all communication – improves both data rate and tracking capabilities
- Used advanced codes to both increase the data rate and reduce the error rate
- Used a packet-based scheme for loading the bit stream
- Together, these resulted in a ten-fold (10 dB) increase in returned bits for Galileo Jupiter operations
- Items in green have continued to be used by subsequent deep space missions

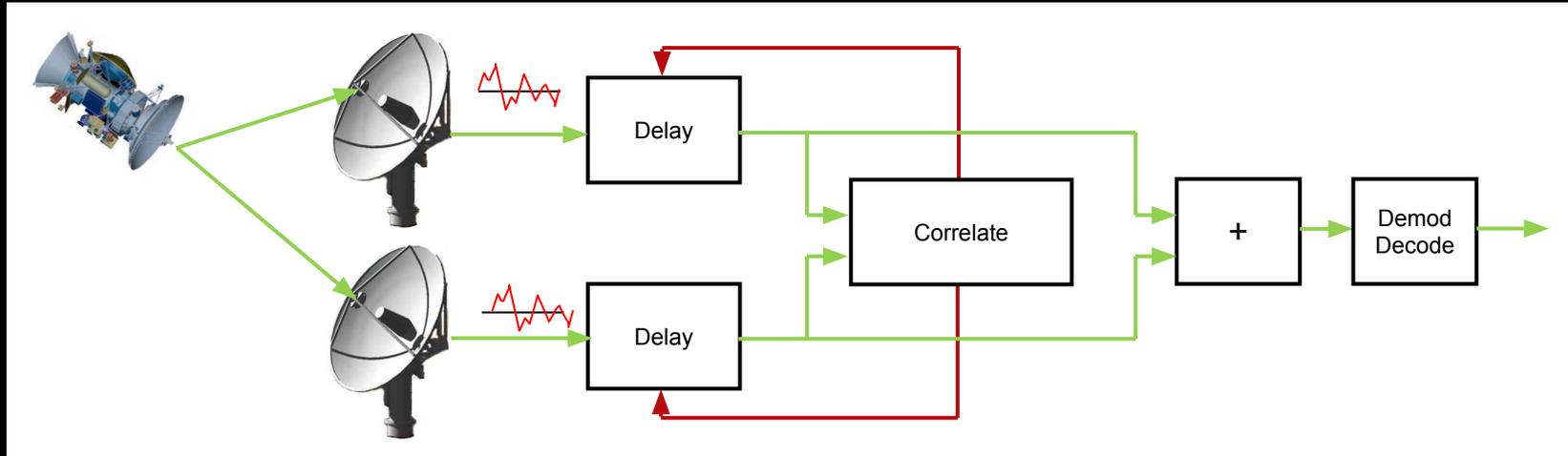
# Downlink Antenna Arraying

Spacecraft signals are received by multiple ground antennas

The common signal between them is corelated and aligned so they can be added together

The resulting summed signal is demodulated and decoded

Performance is close to that of one giant antenna with an area equal to the sum of all the antenna's areas



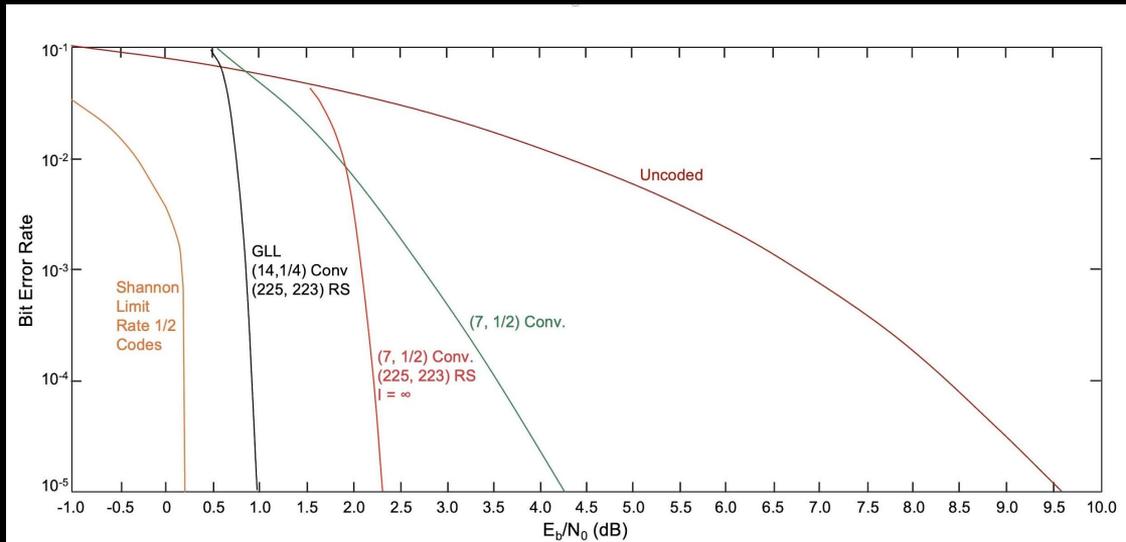
# Error Correcting Codes

An *error correcting code* uses redundancy to control errors on a noisy channel

Trivial example: Repetition codes – just say your message multiple times

Luckily, there are codes that are not this wasteful!

Galileo launched with an excellent code – we designed a better one, implemented in software *after* the existing code



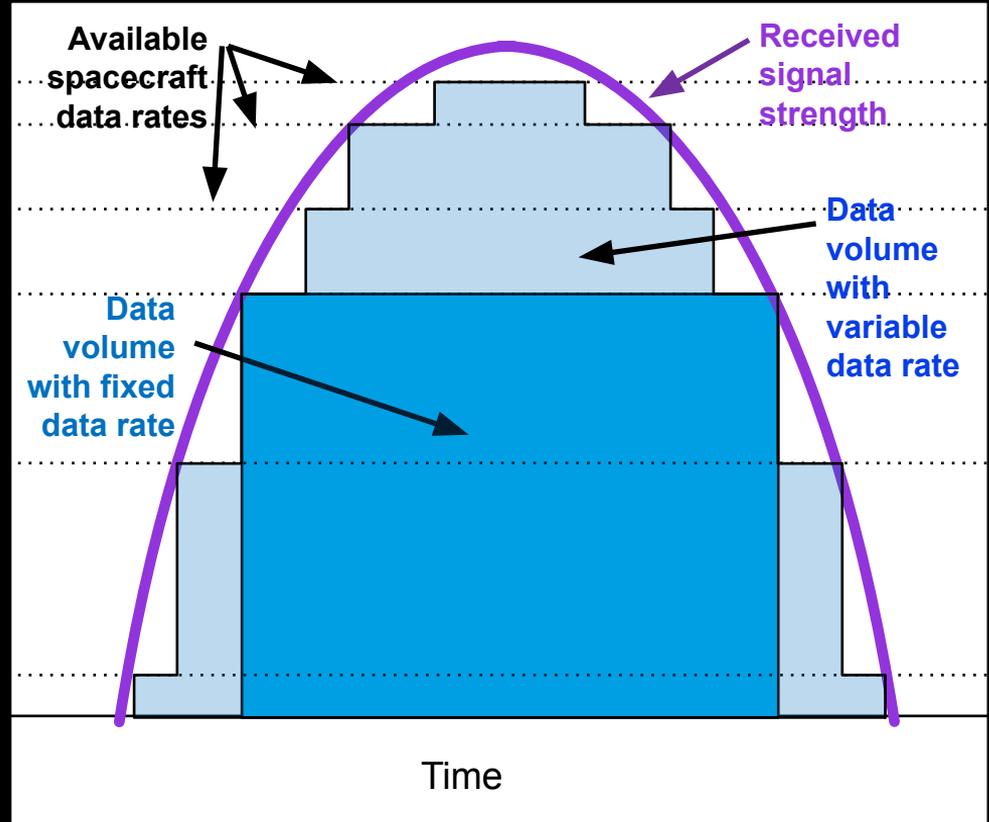
# Compression – Being stingy with bits



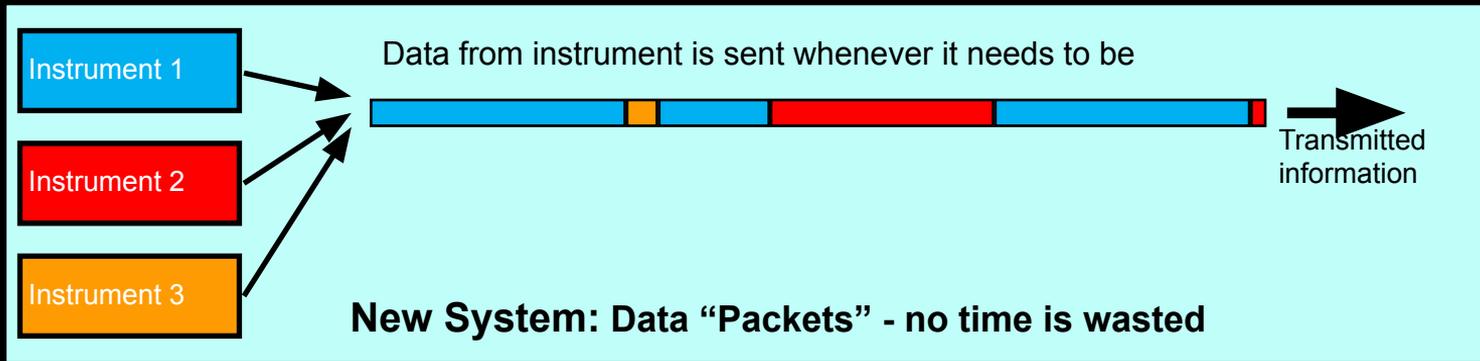
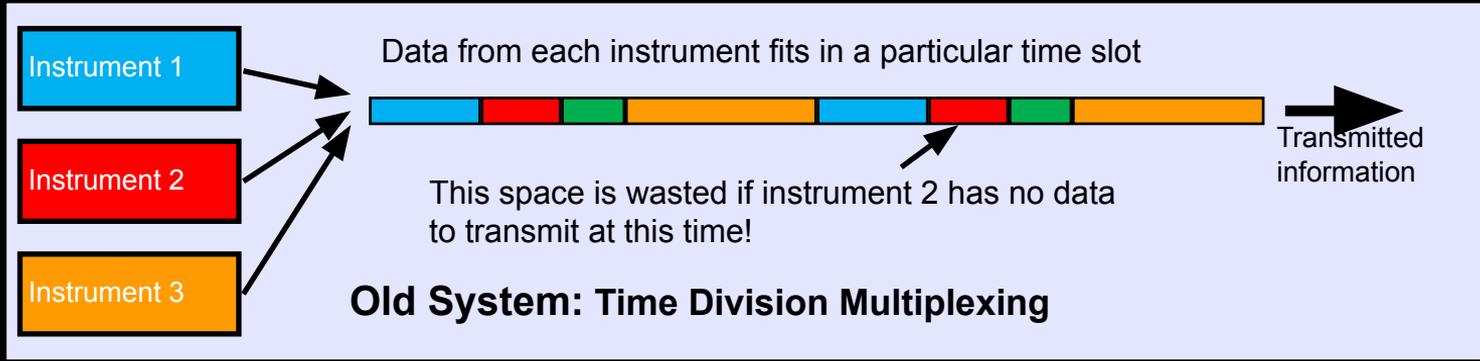
- Data compression is like texting
  - FYI JOE'L BRB 2 HELP L8R
  - For your information, Joe will be right back to help later
  - Compression ratio = 39:24, or almost 2:1
- Galileo Images could be compressed 10:1
  - For other missions, videos and hyperspectral images even more
- Engineering data about 2:1
- Galileo navigation images compressed the most
  - Only needed to return segments of such images and some stellar backgrounds

# Variable data rate

- Before Galileo, we used a fixed spacecraft data rate for each pass over a DSN antenna
- This is inefficient because higher data rates are possible near the middle of a pass
- Changing the data rate fills in the spaces
- This is now a standard technique



# Packet Telemetry



# Conclusion

- The telecommunications link improvements enabled a 100-fold (20dB) increase in data return from Galileo during orbital operations
- Though the number of bits returned in the prime mission was only 1% of that planned, approximately 75% of the science objectives were met
- Most of these improvements have been used on nearly all subsequent deep space missions
  - Galileo had to make the improvements – so it took the risk for many new technologies (at the time) which have become a new normal
- We thank the Galileo and JPL Telecommunications teams for making a major step forward in performance for the set of deep space missions