Experience with Past Outer Planet Missions

Alpbach – Summer Study Program

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Grand Tour

• In 1961 Michael A. Minovitch discovered that planets could provide gravity assist to spacecraft to shorten the time to succeeding planetary targets.

• In 1965 Gary A. Flandro discovered that gravity assist orbits occurred every 175 years that permitted a grand tour of the four gas giant planets, and that the next opportunity would occur in 1977-1979. The grand tour permitted a flight to Neptune in 12 years instead of over 30 years, which a direct trajectory would require.

• A 1965 National Academy of Sciences Woods Hole summer study recommended that NASA de-emphasize human lunar studies and expand solar system exploration.

• In 1970 the Grand Tour mission was proposed for a new start in 1971.
Voyager

• Originally proposed as Grand Tour consisting of two missions; a Jupiter Saturn Uranus mission and a Jupiter Saturn Neptune mission based on the Thermoelectric Outer Planet Spacecraft (TOPS) technology development project.

• However concerns about the ability to achieve lifetime required for the Grand Tour, the extent of proposed new technology, and the cost of such a long duration, ambitious mission caused NASA to cancel the Grand Tour mission.

• JPL quickly counter-proposed a much more modest Jupiter-Saturn only mission with a spacecraft based on the Mariner design using selected TOPS developments, and called it Mariner Jupiter Saturn 1977 (MJS 77).

• In 1978, the name was changed to Voyager and a flexible mission policy adopted that allowed sending Voyager 2 on to Uranus and Neptune, contingent on achieving the prime science objectives at Saturn and Titan with Voyager 1, and contingent on prognoses for a healthy Voyager 2 as the mission progressed.

• This was a sound strategy. It made Uranus and Neptune targets of opportunity that could be funded incrementally, rather than incorporating them as part of the original mission with implications for associated funding and success criteria at the outset.

• But why the names changes; from Outer Planet Grand Tour to MJS 77 to Voyager?
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1 These were modified Rangers
2 These were the first Mariners
3 Viking Orbiters were Mariners
4 Renamed Voyager in 1975
5 Renamed Galileo in 1978
6 CRAF cancelled in 1992
Voyager Development Highlights

• Launched on August 20, 1977 and September 5, 1977 at a then-year cost of $320M. Both spacecraft are still working 35 years later.
• Launched on Titan IIIE-Centauris for total cost of $72M. Project was able to reduce fourth stage avionics and adapter mass and cost by making it an element of the spacecraft instead of the launch vehicle.
• Under the “Atoms for Peace” policy the Project only paid for three of the six RTGs flown and none of the non-recurring cost.
• Original radiation model turned out to be fatally flawed when Pioneer 11 showed Jupiter’s trapped radiation in 1974, which required an expensive and invasive radiation hardening effort after PDR.
• TWTA development; major cost overrun due to manufacturability of new high efficiency cathode.
• Fumes from facility painting 3 weeks before launch required science detector change out on several of the science instruments.
• Voyager flight parameter for max roll rate did not account for launch vehicle programmed roll rate, causing spacecraft fault protection to access redundancy 10 seconds after launch for a nonexistent problem.
Voyager Operations

- Voyager 2 launched August 20, 1977, then Voyager 1 on September 5, 1977.
- Voyager 1, most distant human-made object in space, reached
  - 120 AU in Feb 2012, and is departing the solar system at 3.6 AU per year
  - Heliopause in June 2012.
- Voyager 2, exploring space south of the ecliptic plane, reached
  - 98 AU in Feb 2012, and is departing solar system at 3.3 AU per year.
- Spacecraft details:
  - Power from RTGs was 470W at launch, 280W now; loads are being shed to continue operations.
  - Four of 11 instruments still operating.
  - Likely will have enough power for only one instrument by about 2020, but able to transmit through 2025.
  - Data being sent at 160 bps over 34-m antennas for 16 hours/day.
  - 5 trillion bits received over 35 years, now at $10^{-16}$ Watts received power.
  - Entire launch-cruise-Jupiter-Saturn mission was programmed at launch into two redundant 4096 word memories.
Galileo

• Originally conceived as a Pioneer class Jupiter Orbiter with Probe (JOP) – a spin stabilized spacecraft with a simple despun platform for remote sensing.
• Later, more capable remote sensing was selected which ultimately required a much heavier and more complex dual spin design.
• The DFVLR propulsion system provided major cost savings to NASA and enhanced political support in US, but the
• The dual spin design caused the propulsion system to become bigger and it became a major structural load path, complicating the interface engineering and integration.
• The Project had been directed to use the Shuttle and a new upper stage, but then was plagued by continued Shuttle schedule difficulties and deteriorating performance.
• The spacecraft was launched in 1989, seven years later than the planned 1982 launch and arrived in 1995, ten years after planned arrival.
• In the end the mission was completely successful mission in spite of the stuck antenna.
Galileo in Retrospect

• The 1982 launch opportunity was a uniquely low energy opportunity, occurring every 11 years, with a $C_3$ of only 78 km$^2$/sec$^2$ compared to 80-85 km$^2$/sec$^2$ normally required.

• NASA had decided to discontinue the use of expendable launch vehicles requiring all future missions to use the Shuttle and starting a new upper stage development for planetary launches, which put the Shuttle and the upper stage development on the critical path for Galileo.

• This should have raised a red flag, but it seemed reasonable at the time based on Galileo being the planned 27th Shuttle launch on the manifest and NASA’s intent to develop a 3-stage Planetary Upper Stage based on the Air Force’s 2-stage IUS.

• Then, the Shuttle schedule deteriorated and within two years of project start Galileo became #18, then #15, then #12, then #7 on the manifest, finally forcing NASA to cancel the 1982 launch.

• With the launch energy requirements much higher in all subsequent launch years the planned Planetary Upper Stage would not suffice, leading to four costly spacecraft redesigns, described in the next chart, including the introduction of a Probe Carrier, a Mars Flyby Module and the Centaur upper stage, all of which got scratched along the way.

• In retrospect, considering the schedule risk implied by the Shuttle and Planetary upper stage developments, it would have been a lot less costly had NASA retained the Titan IIIE Centaur capability.
Galileo Chases Jupiter
Surviving 5 Shuttle Related Launch Delays
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VEEGA
Venus Earth Earth Gravity Assist
Single Event Upsets

• The single event upset (SEU) phenomena was unknown in 1977 at the start of Galileo development.
• Our first clue came in 1979 from the Pioneer Venus mission, which was reporting random upsets with their MOS circuitry in flight.
• By the time we became convinced we would have a major problem in space with the 2901 based avionics, the systems were already in fabrication and development testing.
• We started a two prong solution; 1 - go to a new silicon-on-sapphire technology, which would mean abandoning the existing designs and starting from scratch, and 2- develop a new line of CMOS part types that would be pin for pin replacements for the different 2901 part types.
• We started both approaches in earnest, and I tried to get THE other space users of the 2901 series interested in co-funding the development, but to no avail.
• Within a year SANDIA, who had undertaken the CMOS development, was reporting good progress, and we were able to abandon the silicon-on-sapphire approach.
• Ultimately the CMOS replacement proved enormously successful. Later, two of the 2901 users came knocking on our door asking if we had any to spare. Fortunately we did, and so our CMOS parts were also flown on a US DoD satellite and an ESA remote sensing satellite.
• We managed to recoup 2/3 of our original investment, which was a nice acknowledgement that we were right to have been concerned enough to tackle a problem that most people at the time did not believe was an issue.
The Memory Device Debacle

• The Galileo and Magellan projects planned a joint buy of TCC-244 1k RAM memory devices for their AACS and CDS subsystems.

• The first lot of 10,000 packaged parts had to be neutron irradiated to correct different p and n channels leakage effects due to a processing defect, and then the neutron damage had to be annealed using heat from the eutectic die attach.

• After installation in the spacecraft and with the spacecraft at KSC in late 1985 we thought the parts were OK until a failure turned up in a Magellan part in early 1986. The failure was attributed to the eutectic die attach process and we decided to scrap the lot of them.

• A second lot of 10,000 die were packaged using epoxy die attach, but they were scrapped for stress voiding caused by different coefficients of thermal expansion during the lid seal process.

• With only 5000 die left, both projects opted to use a new 4k RAM memory devices, but with quad redundancy for the CDS subsystems, and to use the TCC-244 devices for the AACS subsystems.

• When the new lot was tested, moisture exceeding the MIL spec level of 6000 ppm was found.

• The choice was to redesign the AACS subsystem to use the new 4k RAM devices, or find a way to get rid of the moisture.

• A process to do just that (i.e., punch a hole in the lid of each TCC-244 package, drive the moisture out under thermal vac. conditions, and then reseal) was developed, qualified, and used successfully.

• Ironically, subsequent test and analysis has shown that the original parts would have been OK.

• However this daring solution did solve the memory issue as known at the time, and ultimately saved the Orbiter mission because the quad redundant 4k RAMs provided the added memory needed to add the data compression and coding algorithms to solve the stuck antenna problem.
Cassini

• The progenitor of Cassini was the Comet Rendezvous Asteroid Flyby Mission (CRAF)
• After several failed new start attempts, NASA proposed a dual mission using the same basic spacecraft design for both missions hoping to consolidate the science community and the Congress behind a new CRAF/Cassini mission.
• It worked – for awhile, but then CRAF was cancelled, and Cassini was descoped, to fit within the emerging budget.
• ASI joined NASA as a partner to provide the antenna, several critical r.f. components, and elements of the radar.
• ESA came forward with the Huygens Probe forming the Cassini-Huygens Mission.
• The spacecraft was launched in October 1997, arrived at Saturn in 2004, is still fully functional, now in its 2nd extended Mission with a plan to impact Saturn in 2017 to end the mission.
• The Huygens Probe reached Titan in January 2005, entered the atmosphere and reached the surface performing flawlessly relaying its data through the Orbiter to Earth.
Some Cassini Cost Control Measures

• Use of a resource trading board to manage the allocation and redistribution of reserves, including cost, mass, power, data rate among the science experiments.
  – It worked well; with the total science payload delivered under mass and cost budget, unlike Voyager and Galileo, but has not been used since, probably due to differing project management styles.

• Use of Firm Fixed Price subcontracts on 20 out of 22 different spacecraft development contracts.

• Use of a “Rec-Del” system to manage 12,000 different spacecraft hardware deliveries.
Outer Planet Mission Challenges

• Long distances – telecommunication round trip light time
  – High degree of autonomy
  – Programmable sequence execution
  – Telemetry recovery during EDL
• Long lifetimes – electronic & mechanical part reliability
  – The quality of electronic parts is a strong factor in spacecraft life – “leave no stone unturned”.
  – Requires rigorous problem reporting system that exposes unverified failures, and does not rely on redundancy in risk assessment.
  – Requires inflight ability to assess, detect, and correct inflight anomalies
• Radiation environment – Ionizing & heavy ion charge (SEUs)
  – Rad hard parts
  – Shielding mass, software error correction
• Number and diversity of science instruments – both in-situ & remote sensing
  – Spin stabilization vs. 3-axis stabilization and pointing.
  – Scan platforms with high precision targeting capability and motion compensation are very costly
• Multiple targets & competing observational strategies – convoluted operational sequences
  – New operational sequence for every target opportunity
  – Science instrument conflict resolution
• Long mission durations – post launch development & continuity of personnel
  – Observational sequences and strategy continue to evolve after launch
  – Requires rapid sequence generation and validation during mission
  – Requires careful definition, control & documentation of spacecraft operational constraints, and enforcement especially in view of unavoidable turnover of personnel; cannot rely on corporate memory