Jet Propulsion Laboratory
California Institute of Technology

2.0113 Data Production on Past and Future NASA Missions

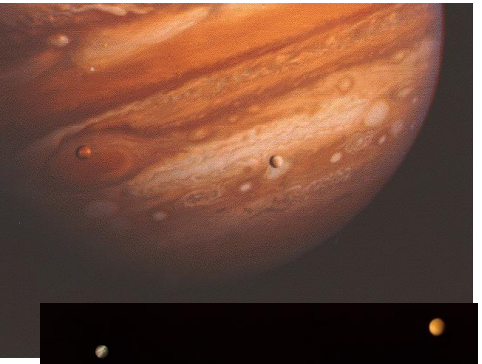
Monday March 6, 2017

Presented by Travis Imken

Written by Lee Jasper and Peter Xaypraseuth

Voyager 1 & 2

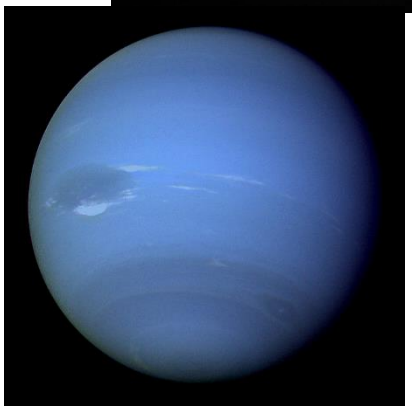
- Voyager 1 & 2: Jupiter and Saturn flybys [13]
- Voyager 2: Uranus and first flyby of Neptune



Discovery of:

- 22 new satellites at the four outer planets
- Jupiter's rings, new information on rings of Saturn, Uranus and Neptune
- Magnetic fields of Uranus and Neptune
- Volcanism on Io, “geysers” on Triton
- Auroral zones on Jupiter, Saturn & Neptune
- Heliopause boundary

Informed next generation of missions



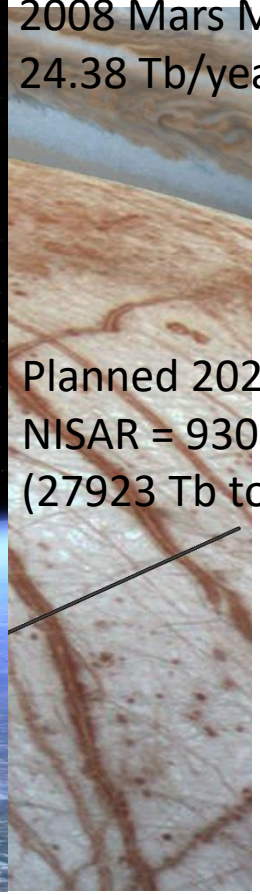
<u>All in about 5 Tb of data!</u>[5]

Yearly Data Return Comparison

Planned 2022 deep space
Europa Mission = 0.86 Tb/year (3.6 Tb total)

2008 Mars MSL Curiosity =
24.38 Tb/year (102 Tb total)

1977 deep space
Voyager 1 & 2 = 0.14 Tb/year (5Tb total)



Planned 2021 Earth
NISAR = 9308 Tb/year
(27923 Tb total)

What Drives Data Return?

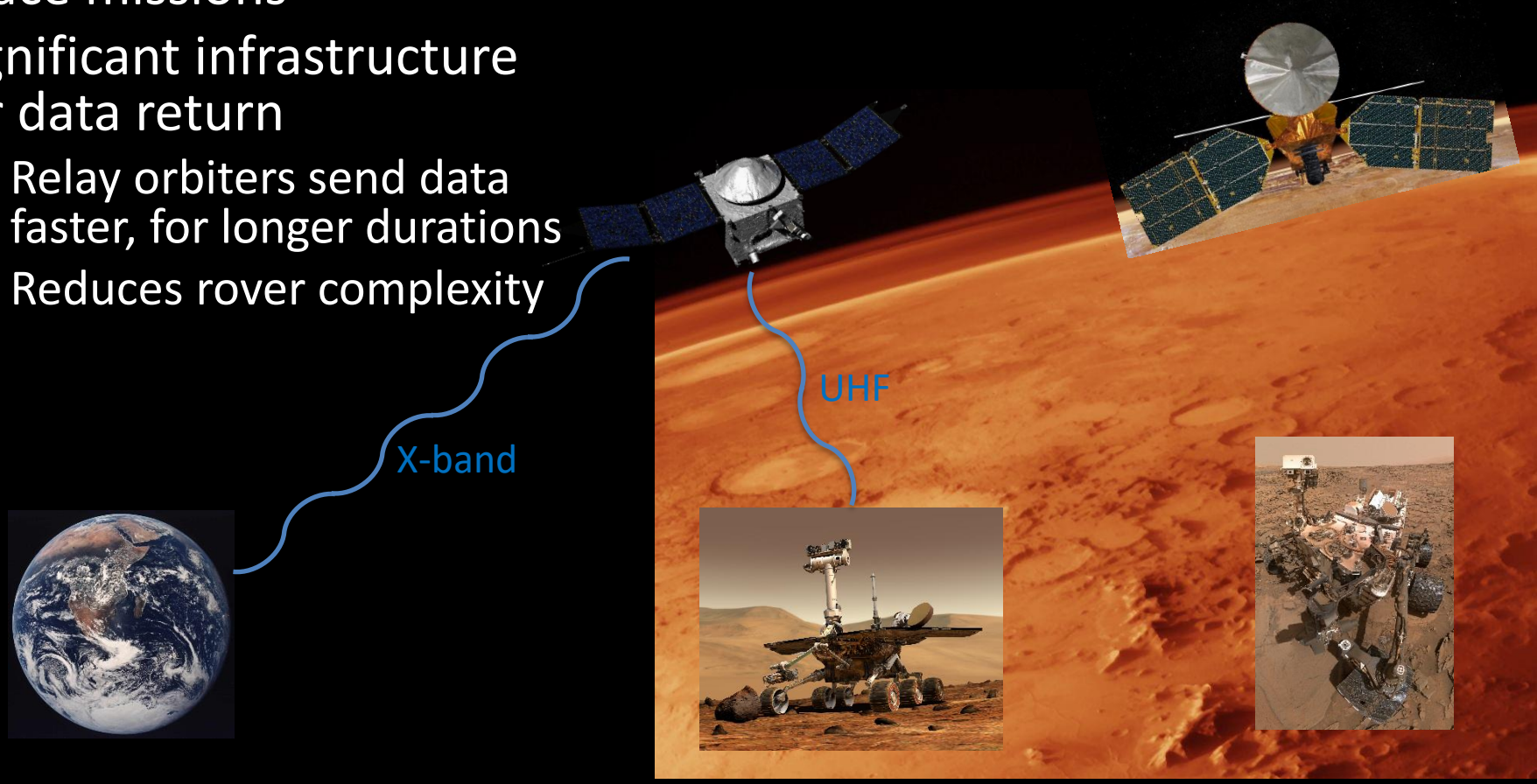
- Two primary technologies throttle bandwidth
  - Telecommunications
  - On-board memory
- Explored how mission capabilities have evolved over time
  - Volume of raw data returned by 17 missions
    - Telecommunication system capabilities
    - On-board memory capacity
  - Ground system capability
    - Availability of ground stations
    - System efficiency by reducing losses, increasing gain

Galileo: Forced Improvement

- Galileo was important scientifically and for the engineering improvements it provided
- High gain antenna deployment failure led to reliance on low bandwidth command/telemetry link
- Caused a 100x improvement in data rates[1]
  - Original data rate at Jupiter: 10 bps
  - Improved compression schemes and encoding brought data rate to 100bps
  - Ground (DSN) arraying and improvements brought rate to 1000 bps
- Lessons learned have been used on all subsequent missions

Mars Missions

- Distinct from other deep space missions
- Significant infrastructure for data return
  - Relay orbiters send data faster, for longer durations
  - Reduces rover complexity

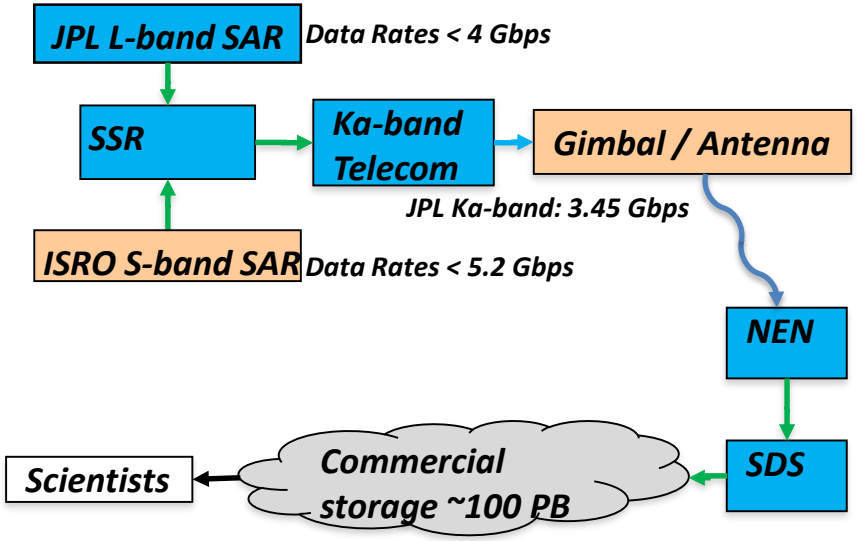


Earth Missions

- Earth orbiters have numerous advantages compared to deep space missions
  - Telecommunications space loss is ~100dB less at Earth or better
  - Greater availability of downlink opportunities (through the NEN and other sites)
  - Less latency of data means less storage duration therefore data can be collected more frequently
- This allows Earth missions to meet signficiant requirements: high-resolution, long-time series, global coverage
  - Missions can downlink each orbit: EOS-Aqua produces about 0.7 Tb/day[28]
  - Missions can behave as “operational” allowing real-time target observation: Landsat-8[27]
  - Missions can dynamically map the Earth with long time series: NISAR provides global coverage every 12 days for 3 years

How NISAR Supports Large SAR Data Production

- NASA-ISRO Synthetic Aperture Radar produces 26 Tb of data per day to study
  1. Ice dynamics: ice sheets, glaciers, and sea level
  2. Ecosystems and biomass changes
  3. Solid Earth deformation including hazard response i.e. volcanoes or earthquakes
  4. Coastal processes in India
- Requires multi-gigabit per second data rates
  - Development of new Ka-band modulator
    - 3.45 Gbps
    - High efficiency LDPC encoding
  - High capacity, simultaneous gigabit per second SSR I/O
    - 12 Tb flash. Completely filled & drained >2 times a day
    - 12 Gbps I/O capability
- Downlink approximately 17 times per day, about 1.8Tb per orbit
- Ground data products balloon to 95 TB per day
  - Over 100 PB for the 3 year mission
  - Using commercially available storage systems, cloud-based storage and access for scientists
  - Tens of gigabit per second data transfers are possible

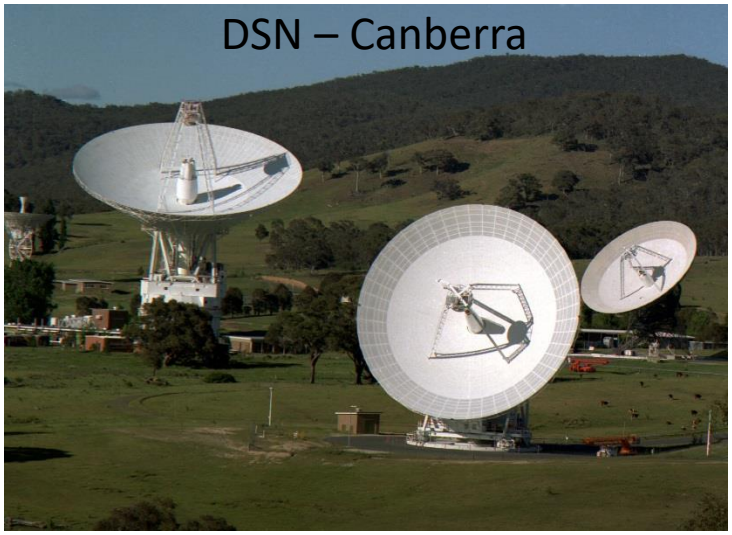


General Trends on the Studied Missions

- Telecommunications
  - Most missions have used X-band since Voyager[4,10,15,24,28]
    - Cassini, Mars Odyssey, MRO, Dawn, Landsat 8, etc.
  - Ka-band systems are up-and-coming
    - LRO, Europa Mission, NISAR
  - Data rates are increasing[6,9,11,22,26]
    - Deep space usually in the hundreds of kbps. Starting to reach Mbps
    - Mars and Earth missions in Mbps. Earth starting to reach Gbps
- Memory
  - Tape drives were used on early missions but have been phased out[12]
    - Could provide large capacity but required mechanisms added failure modes
  - Since early 1990's solid state RAM technology has been primary memory technology[11,23,24]
    - Improvements to density, reliability and radiation tolerance
  - Increased flash memory utilization is likely[7,23]
    - Increased capacity and lower power needs

Ground System Evolution

- The DSN and NEN both evolved from networks established in 1958 and developed from a need to communicate to the probe and human missions
- Both now have multiple permanent sites around the world
- S and X-band are ubiquitous. Ka-band is in development for multiple sites



NEN Sites

DSN and NEN

Evolved with the missions throughout the years

- Early focus: establish network & use cases
  - 64m upgraded to 70m during Voyager
  - Arraying antenna
  - Data transmission with high reliability
- Recent: increasing efficiency & automation
  - 34m antenna now nearly same capability
  - Ka-band Rx/Tx
  - High rate data transfer between the sites
  - Upgrade to optical communications

Ref. [19-21]

Site	Name	Size (m)
Goldstone, USA	DSS 14	70
	DSS 15	34 (HEF)
	DSS 24	34 (BWG)
	DSS 25-26	34 (BWG)
Madrid, Spain	DSS 63	70
	DSS 65	34 (HEF)
	DSS 54	34 (BWG)
	DSS 55	34 (BWG)
Canberra, Australia	DSS 43	70
	DSS 45	34 (HEF)
	DSS 34 - 36	34 (BWG)

- NEN focused on science mission needs
  - Added high latitude stations in the 1990s to support large data volume downlink[16,17]
  - Expand as mission data needs increase
- Expand to lunar & non-LEO missions[15]

Ref. [18]

Site	# of antenna	Size (m)
Fairbanks, Alaska	2 operational	10 - 11.3
North Pole, Alaska	5	5 - 13
Florida	2	6.1
Hartebeesthoek, South Africa	2	10, 12
South Point Hawaii	2	13
Dongara, Australia	2	7.3, 13
Kiruna, Sweeden	2	13
McMurdo, Antarctica	1	10
TrollSat, Antarctica	1	7.3
Svalbard, Norway	3	11.3 - 13
Santiago, Chile	3	9 - 13
Singapore	1	9.4
Wallops Island, Virginia	4	Quad Yagi, 4.7, 11.3
Weilheim, Germany	2	15
White Sands, New Mexico	3	Quad Yagi, 18.3

Data Return by Mission

Mission	Data Produced
Voyager 1 & 2	5 Tb (1977 – now)[12]
Galileo	Est. 0.24 (1989 – 2003)
Cassini	7.86 Tb (1997 – 2017)
DAWN	1.65 Tb (2007 – now)
Juno	1.5 Tb (2011 – 2018 est.)
Europa	2.6 Tb/mission (Planned 3 yrs.)

Deep Space

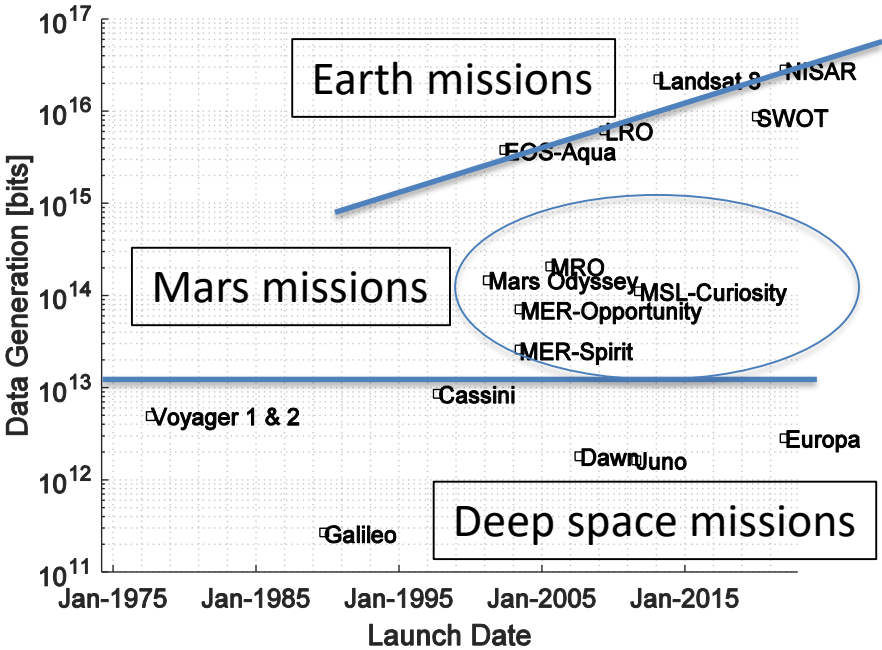
Jet Propulsion Laboratory
California Institute of Technology

Data Return by Mission

Mission	Data Produced	Blu-ray Disc (50GB)	
Voyager 1 & 2	5 Tb (1977 – now)[12]	11.6	Deep Space
Galileo	Est. 0.24 (1989 – 2003)	0.614	Deep Space
Cassini	7.86 Tb (1997 – 2017)	20.1	Deep Space
DAWN	1.65 Tb (2007 – now)	4.22	Deep Space
Juno	1.5 Tb (2011 – 2018 est.)	3.84	Deep Space
Europa	2.6 Tb/mission (Planned 3 yrs.)	6.66	Deep Space
MER – Spirit	23.17 Tb (2003-2011)	49.3	Mars Missions
MER – Opportunity	63.97 Tb (2003 – now)	163.8	Mars Missions
MSL	101.62 Tb (2011 – now)	260.1	Mars Missions
Mars Odyssey	135.34 (2001 – now)	346.5	Mars Missions
MRO	207.5 Tb (2005 – now)	483.1	Mars Missions
EOS-Aqua	3745.05 Tb (2002 – now) [28]	8719.6	Earth Orbiters
LRO	5610.67 Tb (2009 – now)	14363.3	Earth Orbiters
Landsat 8	20064 (2013 – now) [27]	51363.8	Earth Orbiters
SWOT	8,650.5 Tb (Planned 3 yrs.) [26]	20141.0	Earth Orbiters
NISAR	27922.5 Tb (Planned 3 yrs.)	65012.1	Earth Orbiters

Conclusions

- Data production to continue increasing
  - Next class of missions require higher resolution, long time series, etc. to achieve science objectives
  - More efficient encodings and higher rate telecommunications systems developing
  - Larger memory enabled by flash
- Deep space missions will remain in the tens of terabits due to challenges of deep space communication
- Mars has significant infrastructure and will be grouped near hundreds of terabits per mission
- Earth orbiters will see most growth and will continue to produce petabits of data



References

[1] Taylor, Jim, Kar-Ming Cheung, and Dongae Seo. Galileo Telecommunications. Article 5. Pasadena: NASA-JPL/ CalTech, 2002. DESCANSO Design and Performance Summary Series.

[2] Statman, Joseph I., Deutsch, Leslie J. Galileo's Telecom Using The Low-Gain Spacecraft Antenna. Pasadena: NASA-JPL/CalTech, 1996.

[3] Ludwig, Roger, and Taylor, Jim. Voyager Telecommunications. Article 4. Pasadena: NASA-JPL/CalTech, 2002. DESCANSO Design and Performance Summary Series.

[4] Taylor, Jim, Sakamoto, Laura, and Wong, Chao-Jen. Cassini Orbiter/Huygens Probe Telecommunications. Article 3. Pasadena: NASA-JPL/CalTech, 2002. DESCANSO Design and Performance Summary Series.

[5] "Cassini Mission to Saturn" NASA. NASA, 2016. Web. 9 Oct. 2016. https://saturn.jpl.nasa.gov/

[6] Taylor, Jim, Makovsky, Andre, Barbieri, Andrea, Tung, Ramona, Estabrook, Polly and Thomas, A. Gail. Mars Exploration Rover Telecommunications. Article 10. Pasadena: NASA-JPL/CalTech, 2005. DESCANSO Design and Performance Summary Series.

[7] Sosland, Rebekah, et al. "Getting back on the road: Reformatting flash memory on-board the Mars Exploration Rover Opportunity." 2015 IEEE Aerospace Conference. IEEE, 2015.

[8] Taylor, Jim, Lee, Dennis K., Shambayati, Shervin. Mars Reconnaissance Orbiter Telecommunications. Article 12. Pasadena: NASA-JPL/CalTech, 2006. DESCANSO Design and Performance Summary Series.

[9] Makovsky, Andre, Ilott, Peter, Taylor, Jim. Mars Science Laboratory Telecommunications System Design. Article 14. Pasadena: NASA-JPL/CalTech, 2009. DESCANSO Design and Performance Summary Series.

[10] Stephens, Stuart K. The Juno Mission to Jupiter: Lessons from Cruise and Plans for Orbital Operations and Science Return. IEEE Aerospace Conference, Montana, Big Sky. IEEE, 2015.

[11] Stephens, Stuart K., Hirst, Edward A., Nybakken, Derrick J. Juno Project Mission Plan. Revision D. Pasadena: NASA-JPL/CalTech, 2013.

[12] "Did You Know?" NASA. NASA, 3 Mar. 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/mission/didyouknow.html

References

[13] ”Interstellar Science.” NASA. NASA, 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/science/index.html

[14] ”Spacecraft Lifetime.” NASA. NASA, 3 Mar. 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/spacecraft/spacecraftlife.html

[15] McCarthy, Kevin P., Stocklin, Frank J., Geldzahler, Barry J., Friedman, Daniel E., Celeste, Peter B. NASA’s Evolution to Ka-Band Space Communications for Near-Earth Spacecraft. SpaceOps 2010, Huntsville, AL, April 25-30, 2010.

[16] ”History” NASA. NASA, 22 Oct. 2015. Web. 3 Oct. 2016. http://esc.gsfc.nasa.gov/spacecommunications/NEN/gn-history.html

[17] Arko, Scott, La Belle-Hamer, Annette, McCarthy, Kevin, Thoman, Bruce, Tye, Rob. The Alaska Satellite Facility Ground Station. SpaceOps 2012, Stockholm, Sweden, June 11-15, 2012.

[18] Thoman, Bruce E. Near Earth Network (NEN) Users’ Guide. Rev. 2, Greenbelt, MD: Goddard Space Flight Center, 2016.

[19] Taylor, Jim, ed. Deep Space Communications. Pasadena: JPL/Caltech, 2014. Deep Space Communications and Navigation Series.

[20] ”Deep Space Network.”, NASA. NASA, 2016. Web. 3 Dec. 2016. http://deepspace.jpl.nasa.gov/

[21] Jet Propulsion Laboratory. DSN Telecommunications Link Design Handbook. 810-005 ed. Vol. E. Pasadenda: Jet Propulsion Laboratory, California Institute of Technology, 30 Nov. 2000. Web. 3 Dec. 2016.

[22] ”Building the LRO Spacecraft .” NASA. NASA, June 2016. Web. 8 Oct. 2016. https://lunar.gsfc.nasa.gov/spacecraft.html

[23] Ladbury, Ray. Updated Solid State Recorder (SSR) Radiation Guidelines. NEPP Electronic Technology Workshop, Greenbelt, MD, June 11-15, 2012.

[24] Makovsky, Andre. Mars 2001 Odyssey Telecommunications System Handbook. Revision 3.0. PD722-802. Pasadena: NASA-JPL/CalTech, 2001.

[25] Heller, J. A. and I. M. Jacobs, ”Viterbi Decoding for Satellite and Space Communication,” IEEE Transactions on Communication Technology, Vol. COM-19, October 1971, pp 835848.

[26] Telecom Team. ”X-band Telecom Subsystem.” SWOT Preliminary Design Review. Jet Propulsion Laboratory, Pasadena. 18 Nov. 2015.

[27] Sauer, Brian. ”Landsat Operations Report,” Landsat Science Team. U.S. Geological Survey, July 26 2016.

[28] King, Michael D. ”Aqua.” Rpt. in Earth Science Reference Handbook. Ed. Claire L. Parkinson and Alan Ward. Washington, D.C.: NASA, 2006. 73-93.