James Webb Space Telescope Ka-Band Trade

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Abstract – In August 2003 James Webb Space Telescope (JWST) had its Initial Review Confirmation Assessment Briefing with NASA HQ management. This is a major milestone as the project was approved to proceed from Phase A to B, and NASA will commit funds for the project towards meeting its science goals from the Earth-Sun's Lagrange 2 (L2) environment. At this briefing, the Project was asked, "to take another look" into using, the JPL's Deep Space Network (DSN) as the provider of ground stations and evaluate other ground station options. The current operations concept assumes S-band and X-band communications with a daily 8-hour contact using the DSN with the goal of transmitting over 250 Gigabit (Gb) of data to the ground.

The Project has initiated a trade study to look at this activity, and we would like to share the result of the trade in the conference. Early concept trades tends to focus on the "normal" operation mode of supporting telemetry (science and engineering), command and radio metrics. Entering the design phase, we find that we have the unique ranging requirement for our L2 orbit using alternating ground stations located in different hemispheres. The trade must also address emergency operations (which are covered when using the DSN).

This paper describes the issues confronting this Project and how the DSN and the JWST Project are working together to find an optimized approach for meeting these issues.

We believe this trade is of major interest for future Code S and other L2 missions in that JWST will set the standard.

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1. INTRODUCTION

The James Webb Space Telescope (JWST) is an orbiting infrared observatory that will take the place of the Hubble Space Telescope at the end of this decade. It will study the Universe at the important but previously unobserved epoch of galaxy formation. It will peer through dust to witness the birth of stars and planetary systems similar to our own. In addition, using JWST, scientists hope to get a better understanding of the intriguing dark matter problem. JWST has a large aperture, ~6.5 m diameter primary mirror with 25 m^2 of clear aperture, with a mission duration of up to 10-years. JWST will continue the National Aeronautics and Space Administration (NASA) tradition of advancing breakthroughs in our understanding of the origins of the earliest stars. Current launch date for JWST is 2011. The JWST collects data from four science instruments:

(1) Near Infrared Camera (NIRCam) developed by the University of Arizona and Lockheed Martin. This instrument operates in the 0.6 to 5.0 μm wavelength range and generates 40 Mega-pixels in a 288 second frame (4 frames per 1152 sec exposure) with 16 bits/pixel,

(2) Near Infrared Multi-Object Spectrometer (NIRSpec) which also operates in the 0.6 to 5.0 μm wavelength range, built in collaboration with the European Space Agency, and generates 16 Mega-pixels of data,

(3) Mid Infrared Instrument (MIRI), build by a US and European team, generating one Mega-pixel of data, and

(4) Fine Guidance Sensor (FGS) and tunable filter built in Canada.

The data collected by the instruments is processed by the Integrated Instrument Manager (ISIM) electronics for averaging and 2:1 loss less compression. The requirements on the communications system are to downlink 229 Gbits of compressed science data and 6.3 Gbits of uncompressed engineering data, for 235.3 Gbits, every day.

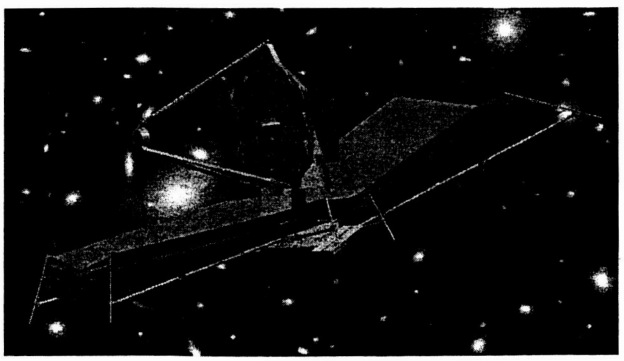

Figure 1 – JWST Artist Conception

Science Data Volume

	Constants	NIR Cam	NIR Spec	MIRI	FGS TF	
Exposure Duration						
Dither Time / Exposure	30					
Readout Duration		12	12	3	12	
Group 0						
Readouts / Frame		1	1	1	1	
Frames / Group		1	1	9	1	
Group N						
Readouts / Frame		1	1	1	1	
Frames / Group		1	1	1	1	
Time Between Groups		200	50	24	200	
Number of Groups		5	80	42	5	
Number of Frames / Exposure		6	81	51	6	
Exposure Duration		1012	4012	1035	1012	
Exposures / Day		83	21	81	83	
Compressed Data Volume (Gbits/Day)		167	116	69	67	
Utilization (%)		100%	24%			
Combined Data Volume (Gbits/Day)						~~196~~
Overhead						
Science Data Packetization	2%					
Reed-Solomon	15%					
Downlink Data Volume (Gbits/Day)						228

167+67=234

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Figure 2 – Science Data Volume

2. CHALLENGING ISSUES

The issues that confront the JWST Project are; (1) Radio Frequency (RF) spectrum issues relating to supporting 8 Mbps in the near-Earth (Category A) X-band (8450 – 8500 MHz) spectrum, and (2) the DSN's reluctance to commit to a minimum of 8 hours per day coverage. The RF concern is that the 8450 to 8500 MHz spectrum has a 10 MHz user bandwidth constraint (see References 3 and 4). With the 8 Mbps data rate and QPSK modulation there is a very good potential for interference to other missions. The solution here is to use a bandwidth efficient modulation scheme and data filters, or move to a frequency band that doesn't have the bandwidth constraint. The second concern, DSN coverage, is that the DSN only has a single 34M antenna at each of their complexes that can simultaneously support JWST's S- and X-Band data links, and their mission support loading beyond 2010 is unknown.

JWST, and other future missions to the Earth-Sun's L2 position, pose a new challenge from previous missions scenarios - in that, deep space missions generally transmit low data rates from long distances and many Earth orbiting missions transmit high data rates. These L2 missions will be transmitting large amounts of data from a greater distance. While the current DSN, GN and commercial networks support S- and X-bands they do not support the new Ka-band frequencies allocated (25.5 to 27 GHz) to allow for high data rates from L2. Due to high G/T requirement needed for the higher downlink data rates, this limits the available ground station providers.

3. JWST & DSN STRATEGIC ALLIANCE

In 2002 NASA reorganized its space communications assets when they decided to abandon the CSOC contract, and distributed the management of NASA's networks to specific

Headquarter offices. The Deep Space Network was assigned to the Office of Space Science (Code S) who is also responsible for JWST. The JWST and DSN struck a strategic alliance in which the DSN would like to support JWST and use it as a model of "how to support a high data rate mission".

The JWST Project invited the DSN to participate in the concept phase design study. During this phase the DSN expressed a concern over JWST's requirement of an 8 hour (minimum) contact a day (232 Gbits at 8 Mbps). The DSN suggested reducing the contact time by increasing the downlink data rate and moving to the recently allocated spectrum of Ka-band (25.5 – 27 GHz). The DSN currently supports Ka-band in the 32 GHz range that is allocated to deep space missions distanced more than 2 Million Km from Earth. Using Ka-band will provide the necessary bandwidth for JWST's high data rate without the X-band bandwidth limitations. In addition, Northrop Grumman Space Technologies (NGST) has suggested using Ka-band and their request has been forwarded to the appropriate NASA committee. The DSN and JWST agreed to cost Ka-band implementation. The DSN infrastructure upgrades were about 15 million dollars. JWST cost estimate for a 100 Mbps Ka-band link was about 28 million dollars. These costs were a rough-order-of-magnitude and will be refined if the decision is to proceed.

Because of these cost estimates the JWST project manager decided not to pursue Ka-band and to continue using X-band.

4. RF Spectrum & DSN Support limitaions

In order to meet the navigation requirement for the L2 orbit there is a need for ranging from two ground stations, one located in the southern and northern hemispheres. Building 2 ground stations means that half the time one is not used (see paper by Fatig, Gal-Edd). All options for JWST included the DSN. Either a scenario of the DSN as the only provider, or building a JWST dedicated station and using DSN for ranging and overflow.

X-band for Space Science missions (category A) is restricted to a 10 MHz bandwidth in the frequency range of 8450 – 8500 MHz. The requirement to send 8 Mbps within this bandwidth could not be met due to masking requirements. To mitigate this problem we decided to eliminate convolutional encoding to recover half of the bandwidth since we had enough link margin by using the DSN 34 meter antenna. The second item was to change the modulation scheme. The current spacecraft design uses QPSK modulation, which does not meet the spectrum requirements. This problem could only be resolved, if they remained at X-band, by using GMSK (Gaussian Minimum Shift Keying) modulation. GMSK modulation has not been used on a NASA mission. The European Space Agency is planning to use GMSK on their Herschel and Planck missions in 2007.

In July 2003 the JWST Project held its Mission Definition Review (MDR). As part of the MDR conformation process NASA's Code S management asked the JWST Project to reevaluate their need for 8 hours of daily DSN support. The Project initiated a trade study (reference 2) which suggested that leasing a ground station is more cost effective than building a ground station, and allows adjustment to technology development and schedule.

In preparing for the Systems Requirements Review (SRR) in December 2003, we realized that the downlink requirements (235.3 Gbits) did not include the 17% communications overhead. If the Project stays with a downlink data rate of 8 Mbps this would require a station contact of 9 ½ hours/day and the possible use of two ground stations.

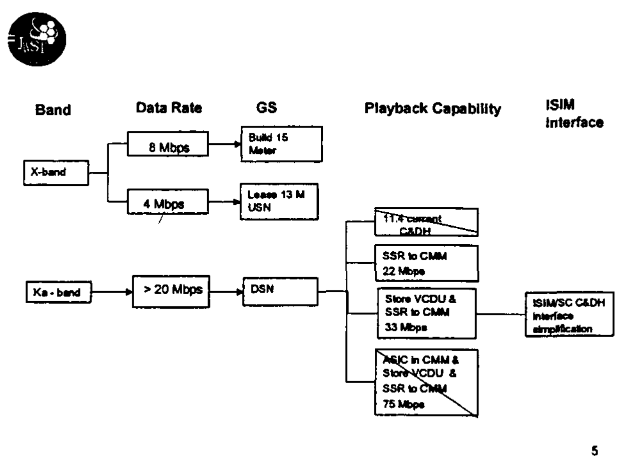

Figure 2 – JWST Communication Trade Study

5. Trade Study Options

The trade options are:

1. Option 1 - Build:
   -Build a 15 meter X/S-band antenna in Canberra,
   -Downlink rate at 8 Mbps,
   -Reduce transmitter power from 50 to 23 watts,
   -Coverage time of 9.5 hours per day,
   -Ranging by DSN,
   -Backup/Emergency – DSN.

2. Option 2 - Lease:
   -Lease X/S-band antennas from commercial vendor (USN, Data links)
   -Downlink rate at 8 Msps, 4 Mbps Convolutional encoded,

-Maintain original proposed RF system (50 Watts),
-20 hours a day coverage (13-meters),
-Ranging by DSN,
-Backup/Emergency – DSN.

3. Option 3 – Implement Ka-band:
-Implement Ka-band capabilities in the DSN
-Downlink rate at 28 Mbps,
-3 hours a day coverage,
-Ranging by DSN,
-Requires Ka-band spacecraft upgrade.

Assumptions:
1. Ninty-five percent availability
2. Ground system at Canberra
3. Cryo-cooled LNAs except for 13 meter
4. X-band elevation angle at 10 deg. K-band angle at 20 deg .

Frequency	Receive system	Data rate (Mbps)	Support period	Coding	Margin (dB)	EIRP Dbw (Power/Antenna)
X	34 M	6	8 hrs	R/S	9.2	46.2 (23W/1.25M)
X	15 M	8	8 hrs	R/S	5.2	49.6 (50W/1.25M)
X	13 M* USN	4	16 hrs	R/S Convol	6.5	46.9 (50W/1.25M)
Ka	34 M**	20	3.2 hrs	R/S	4.2	45.4 (35W/.75M)

*At Hawaii

** 2 dB pointing loss included

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Figure 3 – Options communications link margins

6. KA-BAND – A SYSTEM TRADE

An alternative to building additional X-band ground stations is to stay with the DSN and reduce the contact time.

The previous trade called for a 100 Mbps Ka-band capability, which impacted the entire C&DH and I&T system to handle the increase data rate and was estimated at 28 million dollars. The Project requested Northrop Grumman (NGST) to present several Ka options for consideration.

As the mission design progresses mass and power have become a major constraint. Ka-band is an approach to meet the same data rate requirements with reduced EIRP (power and or antenna size). We could use a 5 Watt Ka-band system as opposed to a 25 Watt X-band system to support the 8 Mbps. Without the spectrum issues of X-band, Ka-band allows an increase in link margins by using convolutional encoding.

The Project Manager directed the study team to focus on reducing the DSN contact time by increasing the data rate range to 20 –50 Mbps. The NGST engineers performed another trade to build a Ka-band communication system that meets his request. The approach is to replace all X-band components with Ka-band hardware.

The conclusion is that in Ka-band the amount of data is linear to the power up to range <100 Msps. As far as hardware components are concerned the Ka-band modulator is the most significant item that will require development and oversight. The Ka-band traveling-wave-tube amplifier (TWTA) has strong heritage from previous programs. The Ka-/S-band high gain antenna (HGA) will have reduced diameter and development efforts are consistent with the baseline X-/S-band HGA. The remaining parts (hybrids, switches, isolators, filters) will transition to Ka-band with a minor increase in complexity. The NGST engineers have indicated that there will be an impact to I&T efforts due to additional test sensitivities at the Ka-band frequency and modifications to the ground support equipment (GSE).

One of the options under consideration is a 20 Mbps system using a 35 Watt transmitter (rather than 50) and a 2 foot rather than a 4.1 foot spacecraft antenna. We are awaiting the cost of communication system upgrades, but they seem competitive to the X-band system with GMSK.

Ka-Band Communication System for ~20Msps

- Maintain baseline S-band transponder
- Ka-band modulation
  - associated X-band hardware string replaced with corresponding Ka-band hardware

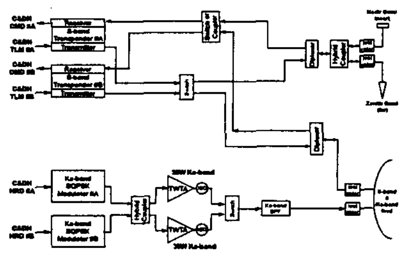

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Figure 4 – JWST Proposed Ka Communication System

Moving to Ka-band and increasing the data rate beyond the baseline SSR playback rate of 8 Mbps impacts the Command and Data Handler (C&DH) capabilities. The NGST Command and Telemetry Processor (CTP) design will limit the data throughput to around 10 Mbps. This is caused by the CTP formatting of the CFDP in software. The Project is evaluating two scenarios; one for 20 Mbps and one 33 Mbps (VCDU replacing CFDP). The VCDU approach writes to SSR in a format ready for downlink. This way the CTP will not have to reprocess the SSR data as it is downlink.

Design Driver	Change Option	Potential Benefit	Impacts
Support Higher Downlink Rate	1) Bring SSR output directly to CMM	Increased downlink (22.4 Mbps Total)	FSW, CMM, SSR, XPNDR
Support Higher Downlink Rate	2) Store SI data as VCDU's in SSR. CMM creates CADU's w/o FSW	Increased downlink (33.0 Mbps Total)	Generate VCDU: ICDH/ FGS/ CTP or SSR; DSN; XPNDR Simpler FSW
Support Higher Downlink Rate	3) Use ASIC instead of FPGA in CMM for increased clock rate and throughput	Increased downlink rate up to 75 MBPS for above options **	Same as above; Increased CMM design and analysis; ASIC foundry costs

** Options 1 & 2 baselined 33 MHz Clock; Option 3 uses 75 MHz Clock

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Figure 5 – C&DH trade to increase throughput

Once we complete the work on optimizing the spacecraft design we need to continue work with the DSN to improve the ground infrastructure.

7. SUMMARY

The data rate and volume of data transmitted by the JWST from L2 is a first and a challenge. The trade includes the ground segment and flight segment, and various disciplines; Power, Mass and C&DH.

Here are the major conclusions:

1. Include the ground station provider, DSN in this case, early in the design process. The DSN has experienced engineers who understand the issues of spacecraft data communications and handling large amounts of data.
2. L2 navigation requires ranging from two ground stations with a north-south baseline.
3. X-band is limited to a 10 MHz bandwidth, with one ground station and 8 hours visibility the maximum daily data volume, including overhead and convolutional encoding, is 230 Gbits.
4. Ka-band is a system wide trade, it can be used to increase date rate, and/or to reduce spacecraft power and mass.
5. Ka-band is becoming the de-facto standard for missions with high data rates.
6. The DSN ground infrastructure needs to be upgraded to support the increased data rate and the new Ka-band spectrum frequencies.
7. High data volume missions now expect to see their science data faster in the SOC. This means increasing the ground communication data lines between the ground stations and the end user.
8. The C&DH architecture impacts data throughput. JWST implementation of CFDP seemed to cause a bottleneck during the SSR playback process. The new design should strive for a balanced throughput architecture.
9. Murphy's Law works – What can go wrong will go wrong, Oops; we need two ground stations for ranging.. Oops, we forgot overhead in daily volume that pushed us beyond 230 Gbits.

8. REFERENCES

1. Fatig, Gal-Edd L2 operational environment
2. Development of NGST's Ground Systems Utilizing COTS and Commercial Standards, Jonathan Gal-Edd, Curtis Fatig, John Isaacs, Richard Lynch , Space Ops 2002
3. Space Frequency Coordination Group recommendations; 5-1R5 *Use of the 8400-8500 MHz Band for Space Science Research, Category A*, 14-1 *Protection of Deep Space Research Earth Stations from Line-of-Sight Interference in the Bands 2290 – 2300 MHz, 8400 – 8500 MHz and 31.8 – 32.3 GHz,* and 21-2R1 *Efficient Spectrum Utilisation for Space Science Services on Space-to-Earth links; Category A.*
4. International Telecommunications Union (ITU), National Telecommunications & Information Administration (NTIA), and Federal Communications Commission (FCC) rules and regulations.

10. BIOGRAPHIES

Jonathan Gal-Edd has been working at NASA since 1994. His current assignment is the Mission Systems Engineering manager for the James Webb Space Telescope (JWST). JWST is the follow on program to the Hubble Space Telescope (HST) and is now entering the design and development phase (Phase B). Jonathan was also the Ground System Manager for the JWST flight demonstrator called Nexus. Before these missions, Jonathan was a member of the GSFC development team for Earth Observing Science (EOS) information system (DIS). Prior to moving to GSFC from Johnson Space Center (JSC), Jonathan served as the Software Development and Integration Lab (SDIL) Manager, for the International Space Station (ISS) program.

Ed Luers is the JPL Interplanetary Network Directorate's representative to the JWST Project. Ed is a member of the Future Missions Planning Office, which provides potential users with information about Deep Space Mission System (DSMS) facilities, capabilities, and plans, and reviews telecommunications link designs to ensure compatibility with the DSN and aid with procurement of AMMOS services and tools. Ed has been *in the aerospace industry for 31 years, which includes 6 years at the GSFC's Rosman, N.C. tracking station and 25 years in the Deep Space Network. Ed is a graduate of the University of Cincinnati.*