Advanced Systems and Communications Architecture:Phase II Final Presentation (Tasks A&B)

NASA-GRC 1/29/02
NASA-GSFC 1/30/02

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Agenda

	Description	Lead Presenter	Time (minutes)
1.0	Introduction/Overview	Enlow	20
2.0	Requirements Definition: Mission and Architectures	Sroga	40
3.0	Formation Flying Technology Assessment	Capots/Byler/Enoch	80
4.0	Communications Technology Assessment	Silverman/Sroga	80
5.0	OBP vs Comm BW Trade/IS Core Definition	Sroga	40
6.0	Integrated Technology Development Trades/Roadmaps	Team	30
7.0	Summary, Recommendations & Phase 3	Enlow	10
8.0	Splinter Sessions (TBD)	Team	60

Presentation Outline

- *1.0 Introduction/Overview*
- *2.0 Requirements Definition: Mission and Architectures*
- *3.0 Formation Flying Technology Assessment*
- *4.0 Communications Technology Assessment*
  - *–RF Communications Technology Assessment*
  - *–Optical Communications Technology Assessment*
- *5.0 On Board Processing vs Communication Bandwidth Trade/ Information Systems (IS) Core Definition*
- *6.0 Integrated Technology Development Trades/Roadmaps*
- *7.0 Summary, Recommendations & Phase 3*

Hyperlinks (via Slide Show)

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Section 1: Introduction/Overview

David Enlow

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Themes/Goals

- *"Enterprise Need" Driven: Developing Technology for Acquisition and Dissemination of Earth Science and Space Science Data and Information*
- *Means :*
  - *A) Sensing*
  - *B) Computation*
  - *C) Communication*
- *Method: Progressive Evolution ------------Revolution*

Case for Evolution

- *High Probability of Payoff*
- *Progressive Technical Steps*
- *Few Variables in Play*
- *"New science" generally not needed*
- *Refinement of Knowledge Base*

Case for Revolution

- ***New mission potential***
- ***Bandwidth utilization***
- ***Data proliferation***
- ***Data exploitation***
- ***LCC improvements***
- ***Throughput/unit resource -> 50% improvement***
- ***Facilitate cross agency collaboration***
- ***Enables self-healing***
- ***Needs:simulation and test beds to minimize costs - low level of infusion assessment.***

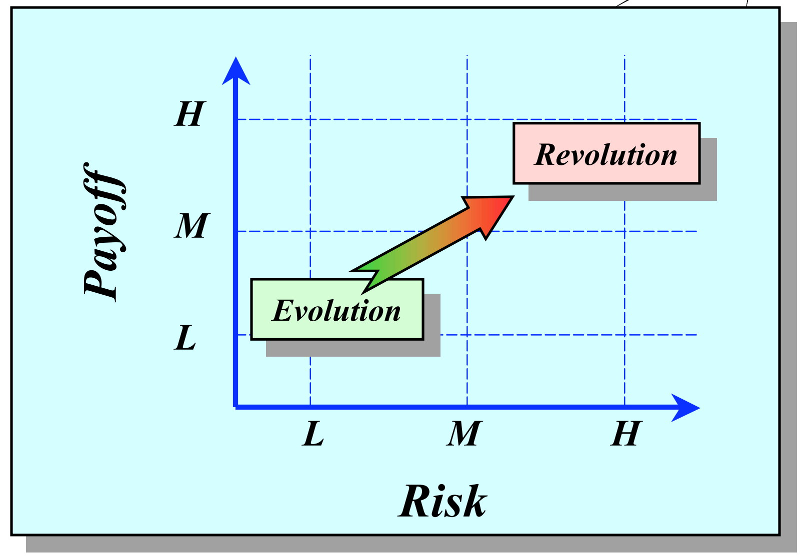
Evolution vs Revolution

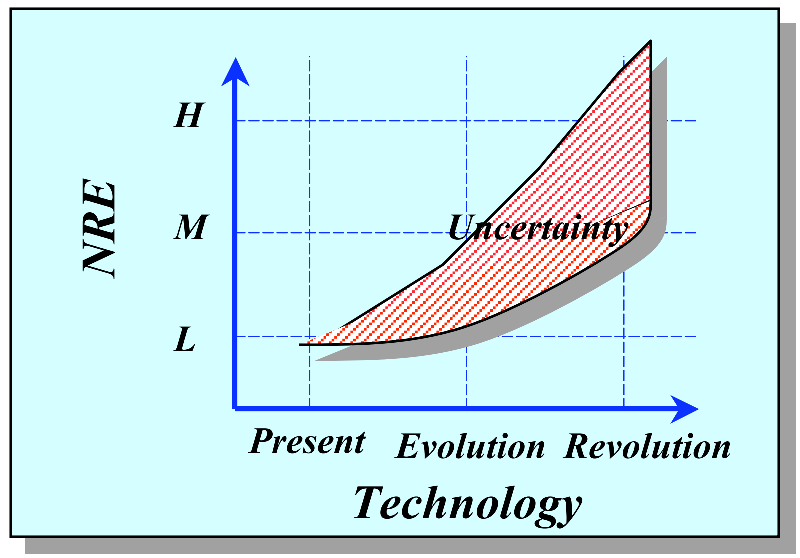
Evolution

- *Lower Noise- Psuedomorphic MHEMPT*
- *50W->100W->120W TWTA*
- *High Power SSPA (>25W)*
- *On Board Processing*
- *Low Noise MBA 7 Feeds*

Revolution

- *RF-MEMS*
- *Superconductivity*
- *Lasercom*
- *Space-based Server (SBS)*
- *Internet in Space*
- *"Receiverless" Architecture*
- *Photonics*
- *Nanotechnology*
- *Quantum Computing*
- *Distributed Mission Ops*
- *Autonomy*





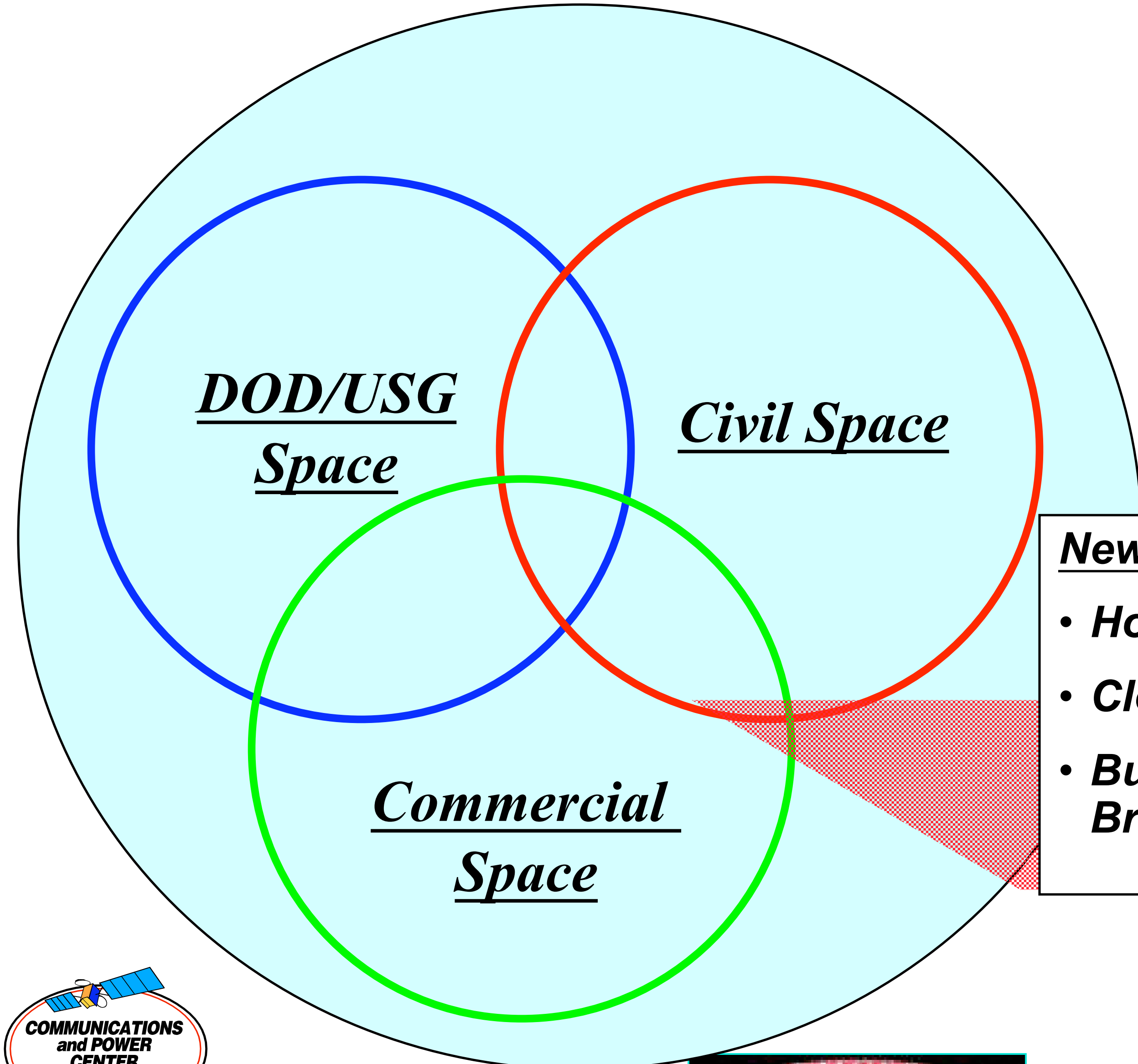
Recent Trends Technology Development

- ***Research and development $ versus $ for J2 fuel and Goretex jackets***
- ***Advanced Concept Technology Demonstration ACTD (DOD version of NMP) usage as means to accelerate technology nugget into service***
- ***ACTD program under active control by elements of homeland defense.***
- ***Technology umbrella to cover Civil, DOD, National Technical Means, and Commercial.***

External Factors

- *Spectrum allocation*
  - *Encroachment*
  - *Congestion*
- *UAV-Space-Ground Connectivity*
- *" Hard Problems"*
- *Transformational Communications Study (cross agency)*
- *Recognition of pooled resources may be cost of revolution*

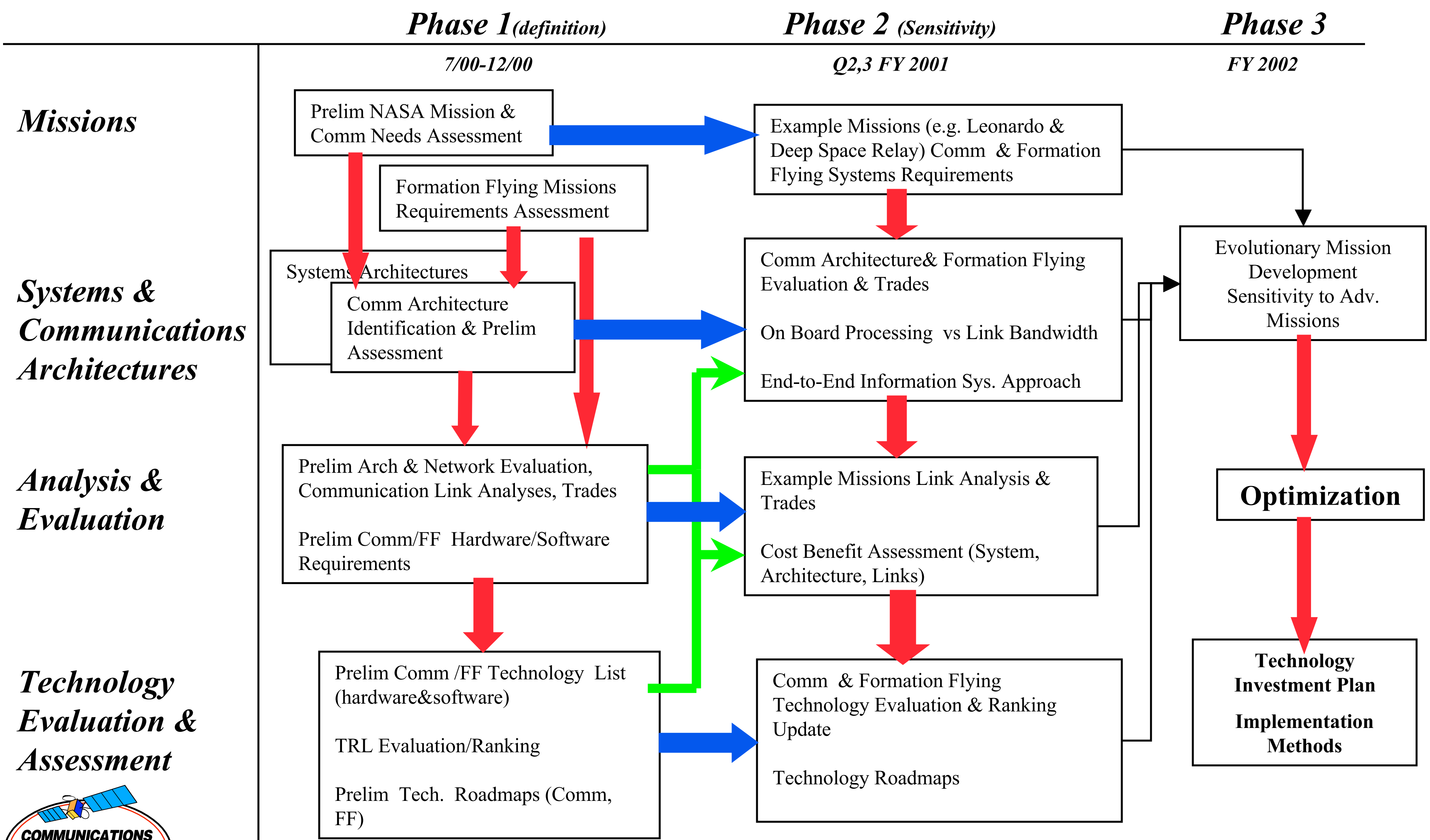
Technology Convergence



New Issues

- Homeland Defense
- Closed Technology
- Budget Growth- Mission Breathe

NASA Systems Communications Architecture & Technology Gap Assessment Study Flow



Programmatics

• Phase 1	6/00-12/00	160K	CPC/ATC
• Phase 2	5/01-2/01	400K	CPC/ATC

- *Supplemental Activities*
  - *NOAA-GOES Adjunct Study (ATC)*
  - *Pascal Definition (Mars-based Proximity Networks)*
  - *Internal IR&D- FF, Advanced networks, Advanced Communication Technologies, and Simulation*
  - *Collaboration with Dr. Warren Wiscombe, PI- LEONARDO GSFC*

Phase II Executive Summary

- **Key Objectives**
  - Identify most promising architecture, corresponding communications and formation flying key and tall-pole technologies, current and needed TRL required, technology gaps and development approach for Future NASA missions.
  - Use strawman mission Leonardo as point of reference.
- **Results**
  - Collaboration with PI is very beneficial process for increasing the utility and affordability of the science mission goals
  - The most demanding element of Leonardo 2015 (L2015) mission is Mission Ops in a Distributed Environment (large integrated cluster of low TRLs and long development times)
  - Architecture for L2015 is Space Based Server/ Sensor Web
  - The Formation Flying Technology Assessment is that a broad range of elements need parallel effort. TRL level
  - The Communications Technology Assessment is that key technologies/ components are identified. TRL level

Integrated Technology Development Roadmap

Process methods

A) Systematic

- *Systems engineering (Goals->Requirements->Performance Specs)*
- *Technology Listing & Options*
- *Technology Performance vs Resources Trade*
- *MOE; FOM; Resource/Risk*

B) Non-systematic - "Mission is King"

Splinter Session Topics

Relevant Lockheed Martin IRAD Topics

- Space Network Simulation: N. Butts
- FF-Ground Based Test Bed Concept: E. Byler
  - Capital Investment (Distributed Space Systems Lab)
  - IRAD (Formation Flying)
- Resource Management Development– GSFC: M. Enoch

Section 2: Requirements Definition: Mission and Architectures

Jeff Sroga

Presentation Outline

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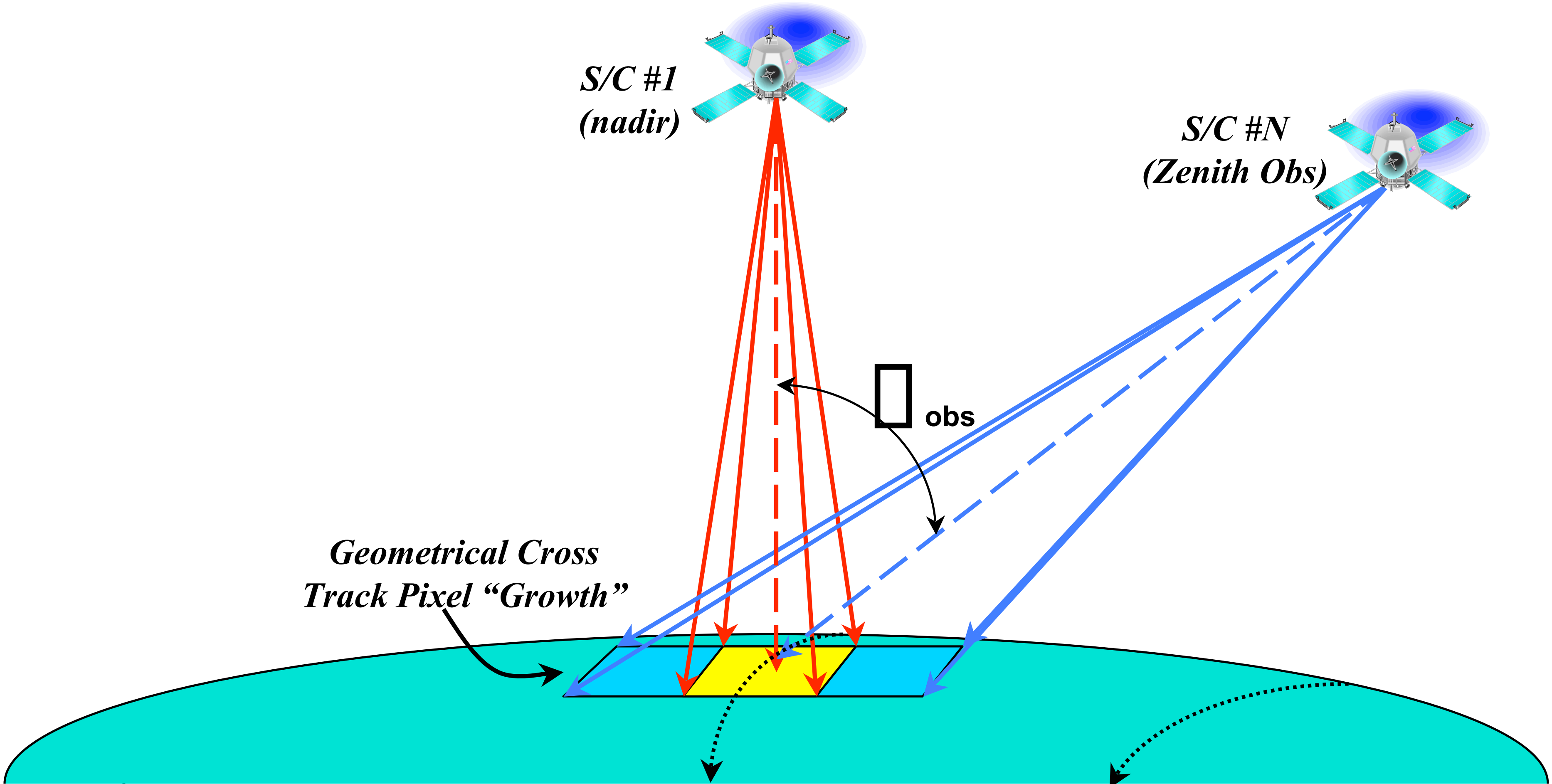
Leonardo BRDF Mission

- **BRDF-Bidirectional Reflectance Distribution Function**
  - –angular distribution of reflected solar radiation
  - –spectral components; temporal & spatial distributions
- **BRDF importance-global climate monitoring/change**
  - –TOA net radiation flux: integral of BRDF over angle space (large angle range)
  - –BRDF uncertainty- largest error contributor for instantaneous TOA fluxes
- **Mission goal: survey and characterize range of BRDF**

http://climate.gsfc.nasa.gov/~wiscombe/LeoBRDF/LeoBRDFhome.html

Coordinated, Multiple Spacecraft Required to Obtain BRDF Data over Large Angular Range

Leonardo "2015" Sensor Observing Geometry



Leonardo "2015 and Beyond" Mission Requirements/Specifications

- ***Phase II effort looked at a future Leonardo type mission (Leonardo "2015 and Beyond") that will push the envelope for formation flying technologies, data communications (crosslinks, dowlinks), on board and distributed data processing, autonomous operations, and advance space network access architectures.***
- ***Leonardo "2015 and Beyond" requirements and specifications are the "baseline" formation flying science mission on Phase II.***

Leonardo "2015 and Beyond" Mission Requirements/Specifications

Formation/Spacecraft:	Description
# S/C in Formation:	6 minimum- maximum 12
S/C Orbit:	400Km Equatorial Orbit (Current Leonardo Concept)
Formation Type:	Loosely coupled (nominal); tighter constraints for higher ground resolutions
Science Operational Requirements	Daytime measurements, simultaneous sampling from constellation S/C along same ground track;
Maximum Link Range:	2000Km (longest link distance)
S/C Pointing Knowledge:	5-10Arcsec (1 Sigma each axis)
S/C Pointing Control:	0.2-0.05 Deg. (1 Sigma each axis)
Timing/Synchronization	<1.0ms
Formation Crosslink Operations:	Autonomous acquisition and tracking Minimum of 2 crosslinks/spacecraft Capable of crosslinking to all formation members
Crosslink Data Rates (Intracluster):	300-3000 Mbps (raw) (possible lower data rate for fewer selected channels)
Network Access Data Rate (Ground/Space)	up to >3Gbps (TBR) (dependent on # connections, architecture)
Network Access Protocols	IP (intra formation & internet) e.g. MobileIP, etc.
Instrument:	
Type:	UV/Vis/Near IR Imaging Spectrometer (pushbroom) 100s-1000 wavelength channels
Ground Track Resolution:	1Km @ 62.5 Deg Nadir (70 Deg Target Zenith) 100-150m resolution @ nadir
Swath Width:	600-700Km nominal
Dynamic Range:	12 bit ADC (minimum)
Raw Instrument Data Rate	~300Mbps- 3.0 Gbps (max)- (depends on # selected channels)
On Board Processing:	
Formation Flying/Maintenance:	Autonomous Operations
OBP Science Data:	Process data to common gridpoint (first level)

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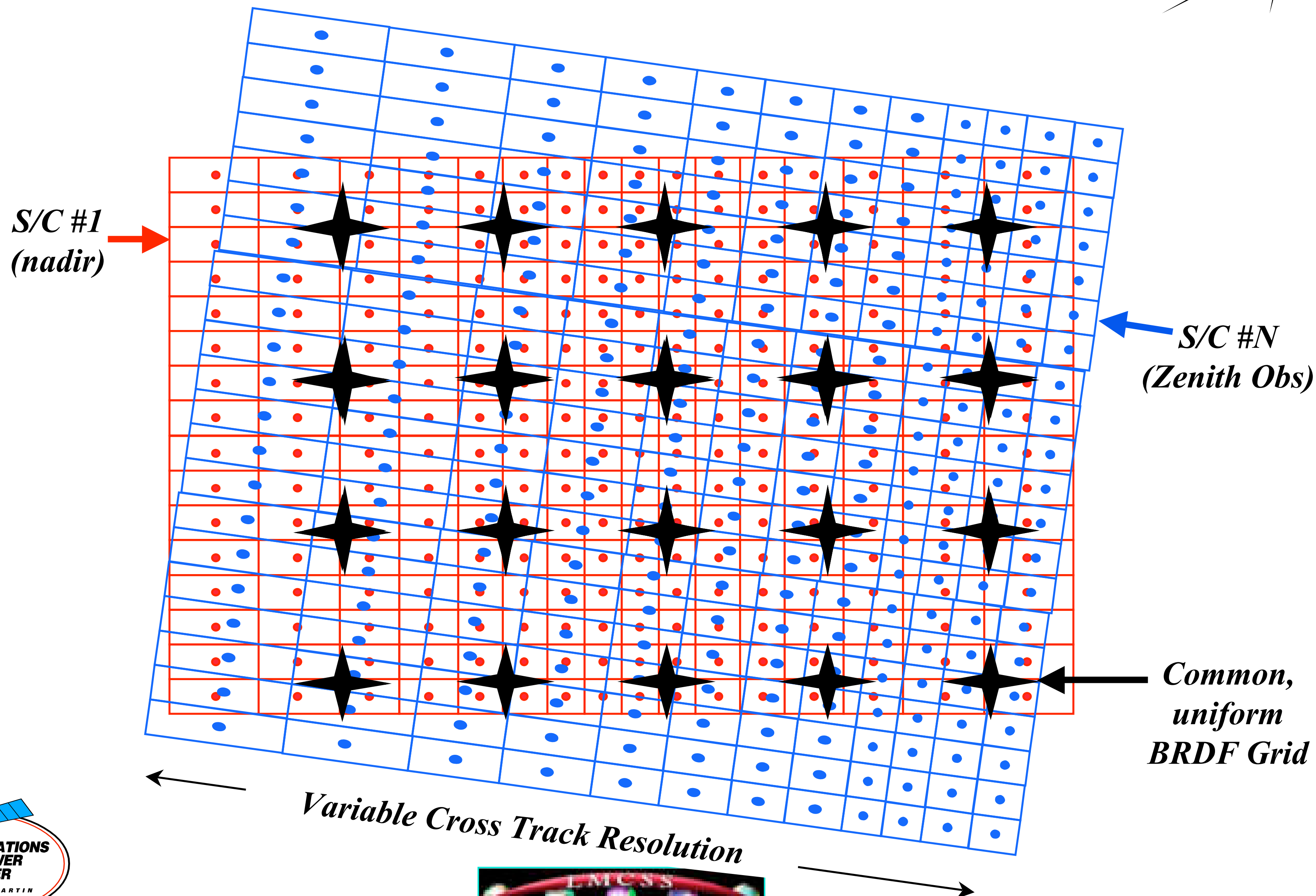
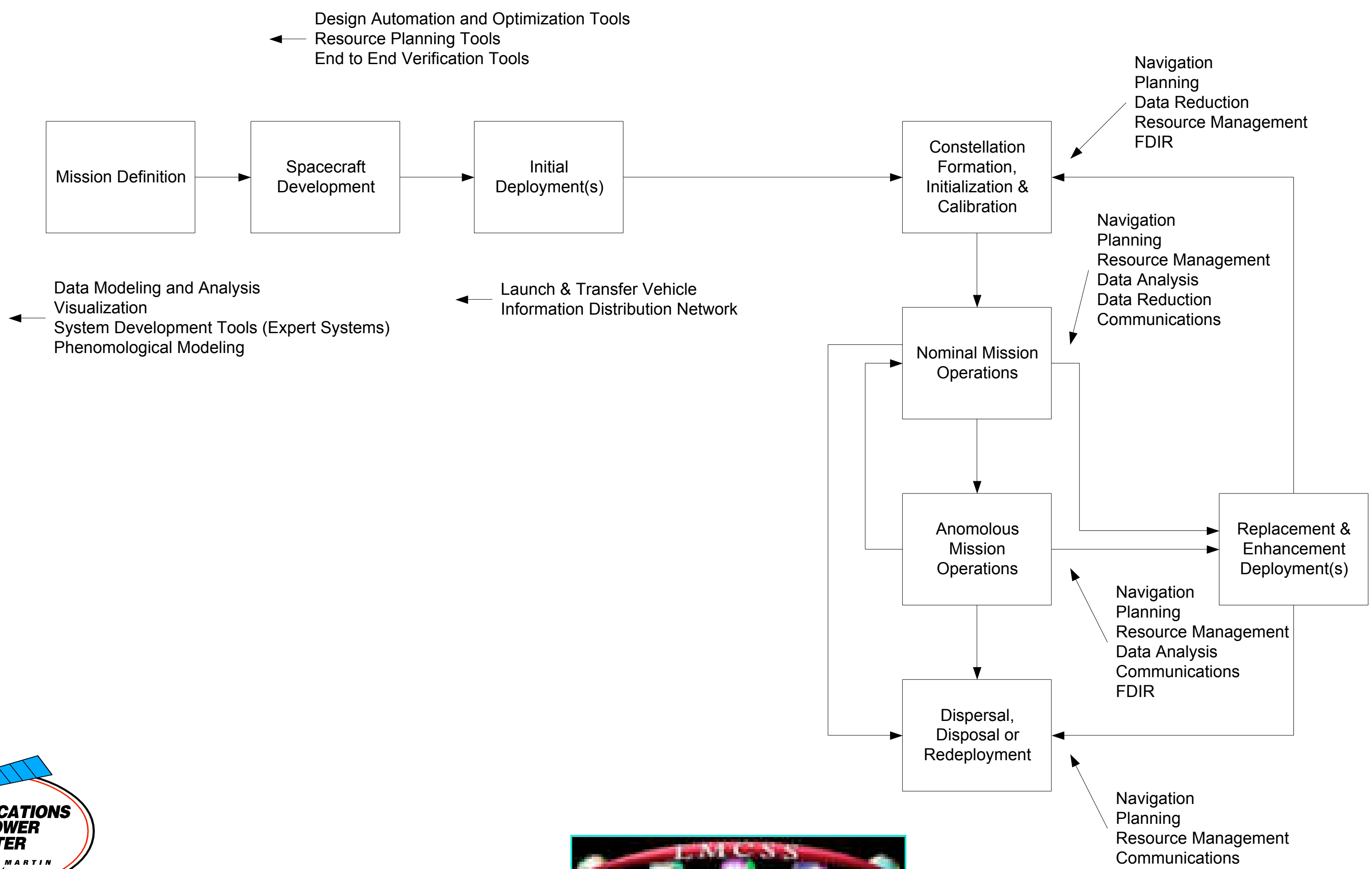
BRDF Data Integration Problem

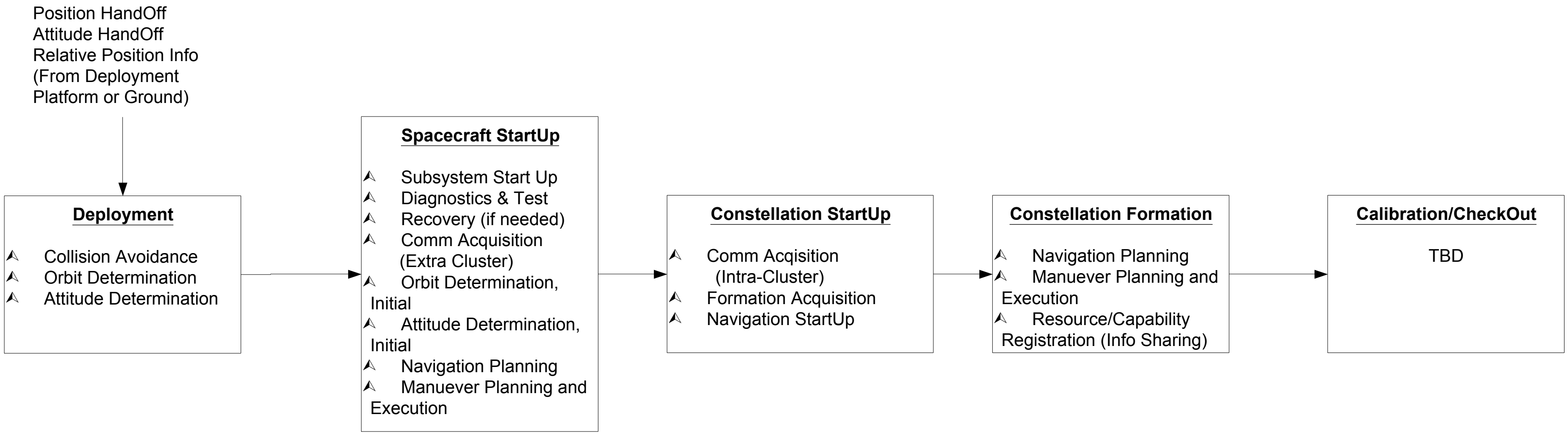


Leonardo Mission Lifecycle

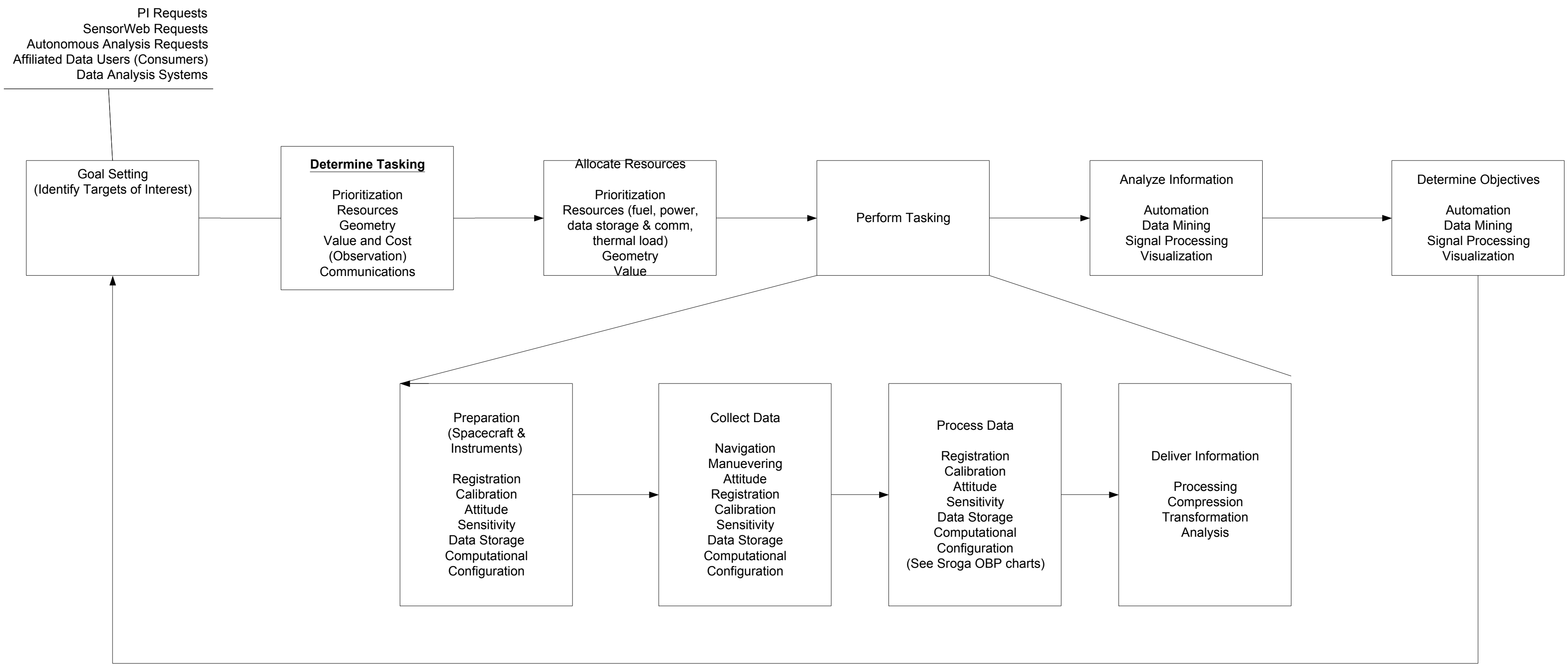
LEONARDO-BDRF Mission Lifecycle Phases



Leonardo Deployment and Initialization

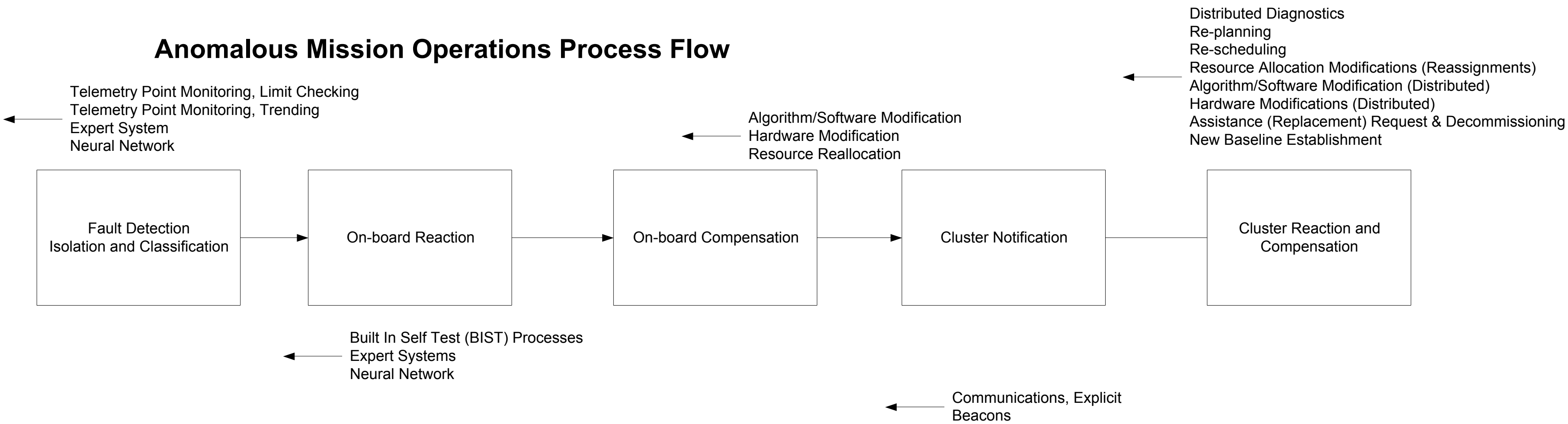


Leonardo Nominal Operations



Mission Anomalous Operations

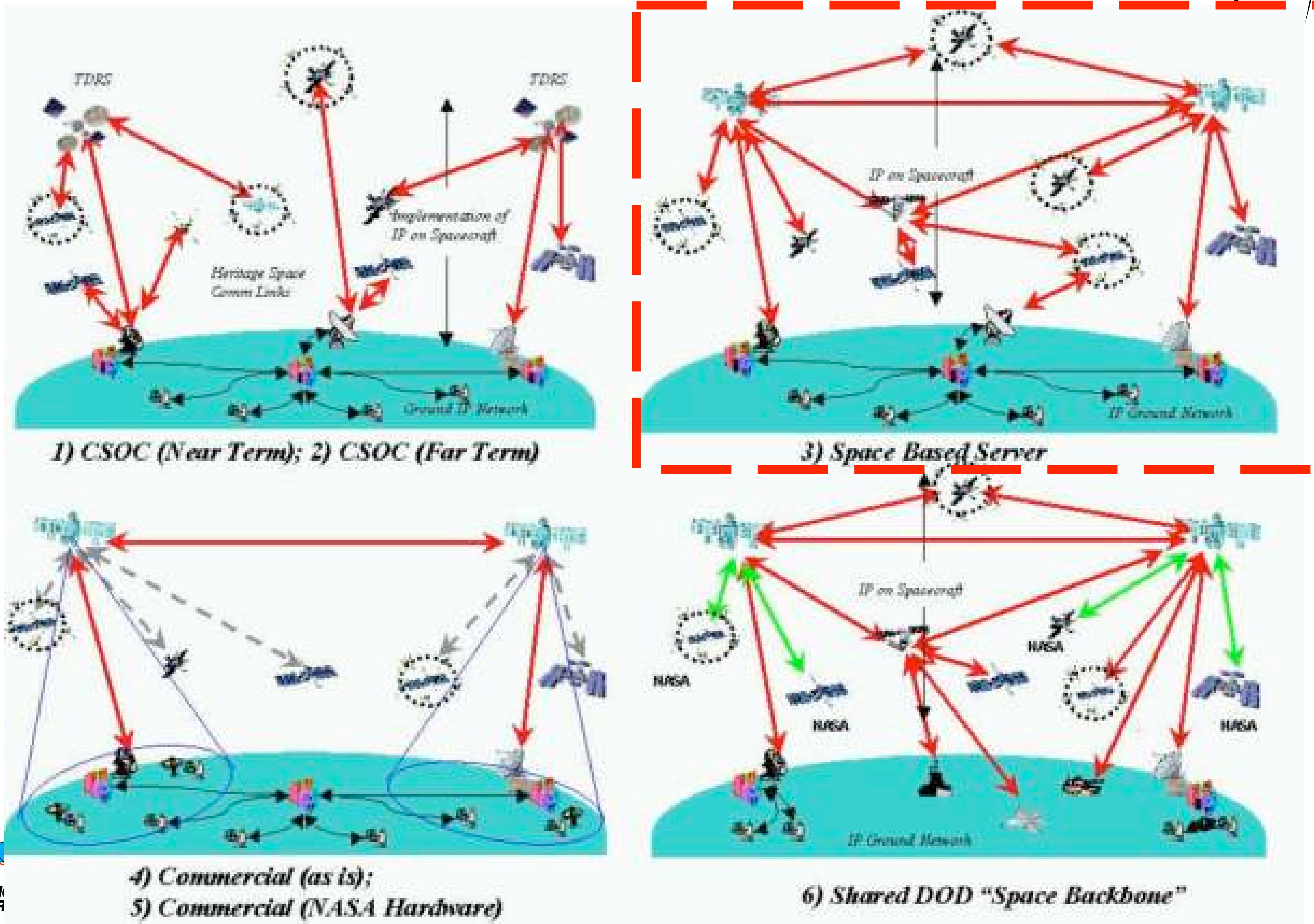
Anomalous Mission Operations Process Flow



Mission Impact on Comm & S/C Flow

	A	B	C	D
	Autonomous Formation Flying Operational Mode	Functional Implementation ("Application Layer")	Information System (IS)/ Comm Systems Impact	Spacecraft Impact
1	Launch & S/C Checkout (individual)	TT&C Communications Health/Status Diagnostics	Ground Control Interaction CMD/CTL Software/AI	TT&C Links Normal single S/C Operations (checkout, deployment, etc.)
2	Formation Initiation and Acquisition	S/C Position/Attitude Knowledge, neighbor position and rate Location Broadcast/Hailing/Beacon Function Autonomous, Coordinated S/C Operations Diagnostics/Feedbacks/Control Loops (formation)	Low Bandwidth/Omni Directional Comm Link Communication Protocols GN&C Comm. Links Distributed CMD/CTL (intra-formation)	GPS Receiver Earth Sensor/Star Tracker Mass/Power Allocation for Low Bandwidth Communications System Actuators & Thrusters
3	Formation Maintenance and Operation	S/C Position/Attitude Knowledge Updates GN&C Communications (intra-formation) S/C Autonomous Operations Diagnostics & Feedback Controls "Target" Area Definition/Location Resource Management (formation)	Low Bandwidth Com Sys., Protocols, ect OBP and Expert Systems Software (FF control) Distributed CMD/CTL communications (network & intra-formation) Command Communications (network & intra-formation)	GPS Receiver/Earth Sensor/Star Tracker Mass/Power Allocation for Low Bandwidth Comm Sys
4	Performance Checkout/Verification			
5	Science Mission Calibration/Validation	FF Operations(above), Science Mission Data Collection (below) Coordinated Observation (space/ground campaign) Cal. Target Observations (Moon, Stars, etc.) Collective Delta V resource management	OBP and Storage (RAM) Calibration Software/Cal. Storage/Updates	Actuators/Thrusters (pointing control) On Board Calibration Source
6	Science Mission Operations	"Target" Area Selection/Decision Observational Strategy/Implementation Science Data Collection Onboard Science Data Processing Data Storage/Delivery	User/Ground (Space Systems?) Request/Commands TT&C Communication Links (commands, requests) Orbit Prediction/Asset Scheduling Software Formation Resource Mgmt/CMD CTL AI software Formation Operations/Maintenance(above) Coordinated Sampling Time Sync/Tagging, Attitude Knowledge Sensor Data, Data Rate and Internal Data Bus CPUs, Router Functions On Board RAM Processing Algorithms/Software (AI) Data Storage (SSR, etc.) High Bandwidth/Directional Intersatellite Links High Bandwidth/Directional Ground Links High Bandwidth/ Directional LEO Space Backbone Links	S/C Data Bus (high speed) Mass/Power Allocation Mass/Power Allocation S/C Data Bus, Mass/Power Allocation Mass/Power Allocations for ISL Mass/Power Allocations for Ground Links Mass/Power Allocation of Space Backbone Links
7	Fault Detection/Management	Health/Status Monitor ("Heartbeat" Function) Distributed "Network" Operations	AI Health/Status Monitor Software	
8	Standby Modes			
9	Survival Modes	Collision Avoidance (beladrun/controlled S/C)	Non-Cooperative Navigation Operation	Collision "transponder" link
10	Formation Augmentation (Decommission, Replacement, Recovery, & Upgrades)	Expandable, Reconfigurable		

Phase 1 Architectures



Phase II Architecture Selection

- *Space Based Server Communications Architecture most promising from Phase I*
- *Advantages:*
  - –*incorporates features of other Phase I architectures*
  - –*open system design (OSI layer model)*
  - –*standard protocols and interfaces (operations, software development/testing)*
  - –*standardized internal S/C C&DH interfaces*
  - –*scalable architecture- growth potential*

Leonardo "2015 and Beyond" Network Access Requirements Trades

Task 1.5 Communications Network Access Assessment

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Leonardo "2015 and Beyond" Point Design Baseline for Network Access Trades

# Formation Spacecraft	6
Spacecraft Altitude	400Km
Instrument Type	Pushbroom Hyperspectral Imager
# Spectral Channels	100
# Cross Track Pixels	4096
Instrument Cross Track FOV	82 Degrees (full angle)
Instrument Swath Width (nadir pointing)	707Km
Cross Track Resolution @ 70 Deg	1Km
Ground Resolution @ Nadir Pointing	139m
# Bits/Pixel	12
Raw Instrument Data Rate	271Mbps (each)
Instrument Duty Cycle	50% (Daytime Only)
Raw Data Volume/Orbit per S/C	753 Gbits or 94 GB
Raw Data Volume/Day per S/C	11,715 Gbits or 1,464 GB

- Multi-purpose Hyperspectral Imager (HSI) utilized for BRDF measurements
- "Feasible HSI" specifications for Leonardo mission - 1Km resolution at 70 degrees zenith angle observation
- Daytime measurements only (50% instrument duty cycle)

Network Access for Processed Leonardo “2015” BRDF Data Output

- *Leonardo 2015 On Board Processing Concept for Top Level, System Data Link Requirements Trade*
  - *data accumulated/interpolated to common, uniform 1Km x 1Km “BRDF” science grid spacing (along, cross track binning)- focus only on end OBP results*
  - *assume on average 50% of instrument swath width in overlap of the formation S/C FOVs*
  - *assume 24bits/”BRDF pixel” to account for increased dynamic range/resolution due to OBP*
  - *OBP for each wavelength channel separately*
- *Per S/C “Processed” Data Rate: 6.5Mbps; Data Volume:18Gbits/Orbit*
- *On Board Data Compression (lossless and lossy) could provide additional data volume reduction-same ratio for “raw” and “BRDF processed” data (not included in this trade)*

On Board “Science” Data Processing for Leonardo “2015” can provide ~40X reduction in Sensor Data Volume

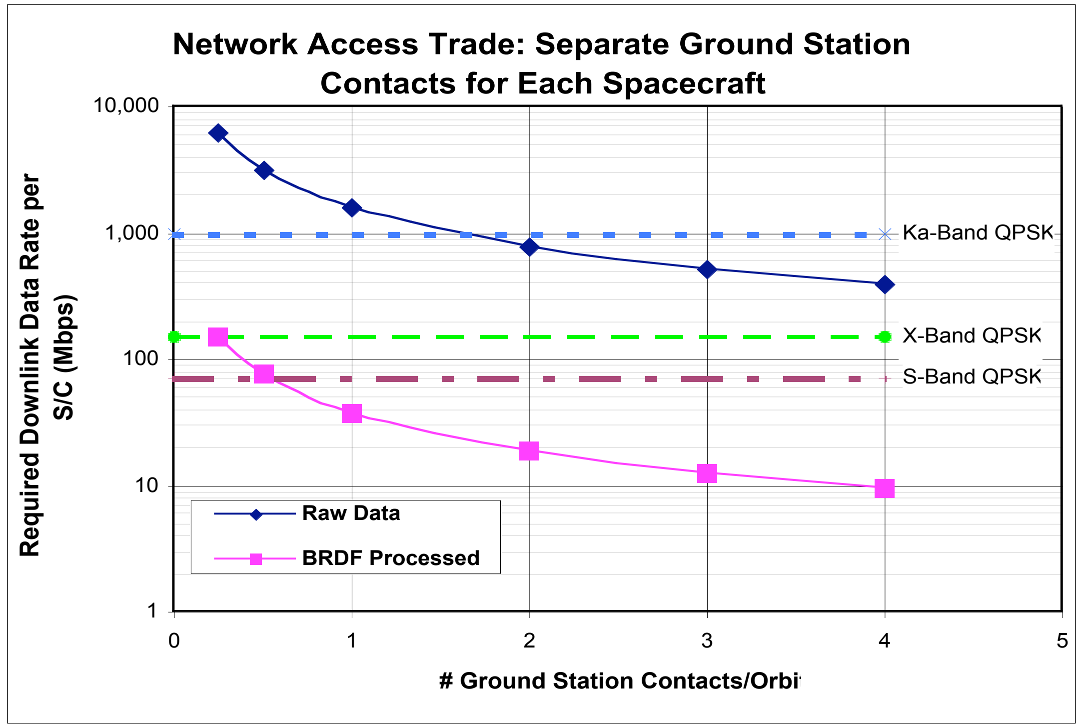
Network Connectivity RF Bandwidth Allocation/Data Rates

Frequency Band	RF Frequency Spectrum Allocations/User Data Rates		Reference
	Space-Ground	Space-Space	
S	79-90MHz BW (2130-2200, 2020-2290MHz)	6Mbps (TDRS S-SA)	http://www.ntia.doc.gov/osmhome/allochrt.html http://nmsp.gsfc.nasa.gov/tdrss/services.html
X	150-185MHz BW (8025-8175, 8215-8400MHz)	N/A	http://www.ntia.doc.gov/osmhome/allochrt.html
Ka	1GHz BW (20.2-21.2GHz)	1GHz BW (32-33GHz); 800Mbps (TDRS Ka)	http://www.ntia.doc.gov/osmhome/allochrt.html http://nmsp.gsfc.nasa.gov/tdrss/services.html
V	N/A	5GHz BW (59-64GHz)	http://www.ntia.doc.gov/osmhome/allochrt.html

- ***Space-Ground, Space-Space frequency allocations from NTIA frequency allocation data base***
- ***TDRSS data rates for TDRSS H,I,J services***

Leonardo "2015" Network Access Trade: Individual S/C Ground Station (GS) Contact

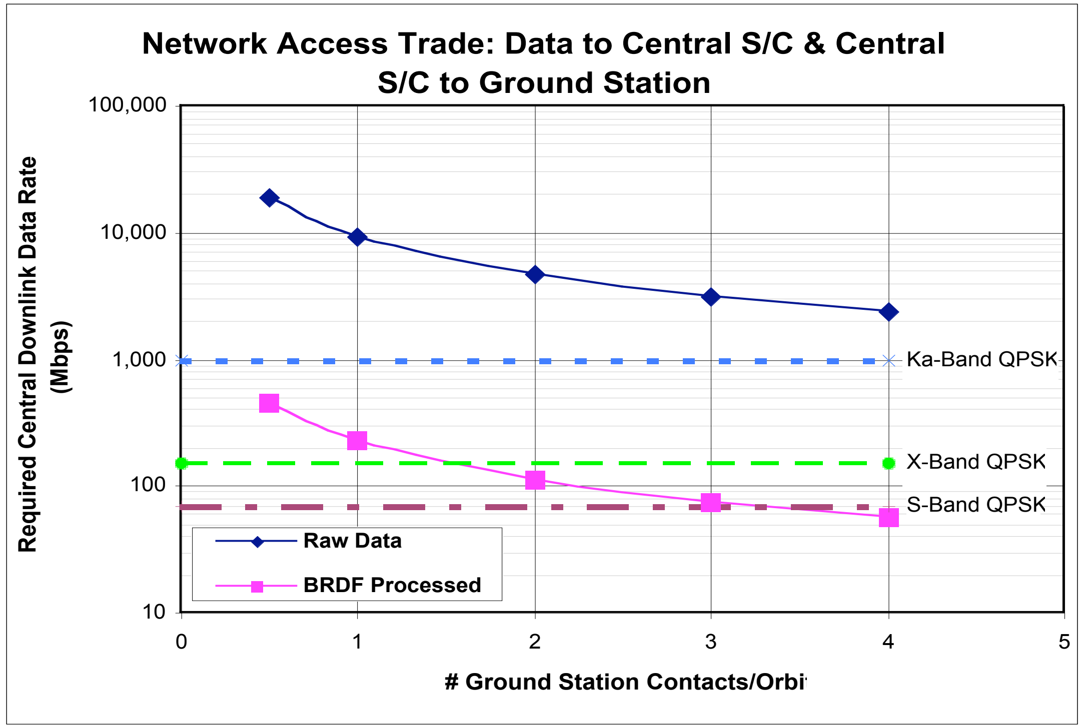
- *Assumptions:*
  - *–each S/C separately downlinks data to ground station*
  - *–8 minute GS contact time*
  - *–Raw Data: all raw data transmitted to ground*
  - *–BRDF Processed: data in overlap regions at 1Kmx1Km grid downlinked*
- *Required downlink capability vs # contacts/orbit*
- *Downlink Data Rate Capacity (conventional technology)*
  - *–S,X and Ka bands*
  - *–max rates for QPSK and frequency allocations*
  - *–encoding and error corrections will reduce downlink "information" rate*



Increased Ground Station Access and/or OBP can Reduce Required Downlink Data Rates for Leonardo "2015"

Leonardo "2015" Network Access Trade: Central S/C to Ground Station Contact

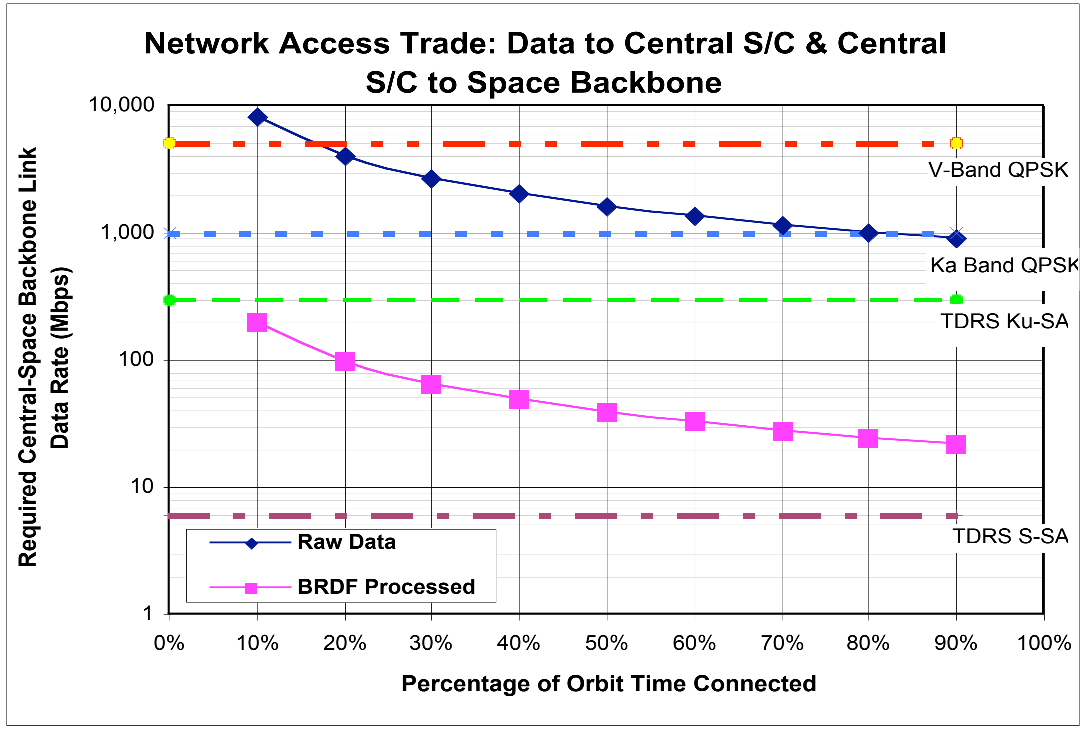
- ***Assumptions:***
  - *–each S/C transmits to "central" S/C and "Central" downlinks data to ground station*
  - *–8 minute GS contact time*
  - *–Raw Data: all raw data transmitted to ground*
  - *–BRDF Processed: data in overlap regions at 1Kmx1Km grid downlinked*
- ***Required downlink capability vs # contacts/orbit***
- ***Downlink Data Rate Capacity (Conventional Technology)***
  - *–S,X and Ka bands*
  - *–max rates for QPSK and frequency allocations*
  - *–encoding and error corrections will reduce downlink "information" rate*



Raw data distribution demands higher order modulation for allocated bandwidth

Leonardo "2015" Network Access Trade:Central S/C to Space Backbone Contact

- ***Assumptions:***
  - *–Each S/C transmits data to "central" S/C and "Central" transmits to Space Backbone (SB)*
  - *–Raw Data: all raw data transmitted to Space Backbone*
  - *–BRDF Processed: data in overlap regions at 1Kmx1Km grid transmitted*
- ***Required IS data rate vs % time connected to Space Backbone***
- ***Space Backbone ISL Data Rate Capability (Conventional Technology)***
  - *–TDRS S, Ku Single Access*
  - *–Ka, V band max rates for QPSK and frequency allocations*
  - *–encoding and error corrections will reduce ISL "information" rate*



Increased SB Access and/or OBP can Reduce Required ISL Data Rates to SB for Leonardo "2015"

Conclusions

- ***Leonardo "2015 and Beyond" Mission Concept -> Large Raw Data Volume Generator***
- ***"Send All Bits" Philosophy:***
  - ***stressing/exceeding conventional downlink capabilities (single S/C and Central S/C concepts)***
  - ***exceeding current TDRSS crosslink capabilities***
  - ***will require reduction in # channels/# pixels/instrument duty cycle and/or on board data compression to fit access capacity***
- ***Bandwidth Utilization (BEM,coding): increased capacity of current frequency allocations***
- ***On Board "Science" Data Processing:***
  - ***concept affords >40X reduction in mission data volume***
  - ***allows "science" data to fit current downlink/crosslink capabilities***
  - ***on board "HSI" compression techniques could further reduce access bandwidth requirements***
- ***On Board Processing Trade to Follow***

Section 3: Formation Flying Technology Assessment

Eric Byler

Michael Enoch

Larry Capots

Presentation Outline

Method

- *Technology Areas (grouped for discussion)*
  - *(A) Missions Operations*
  - *(B) Cluster Communications*
  - *(C) Spacecraft Infrastructure*

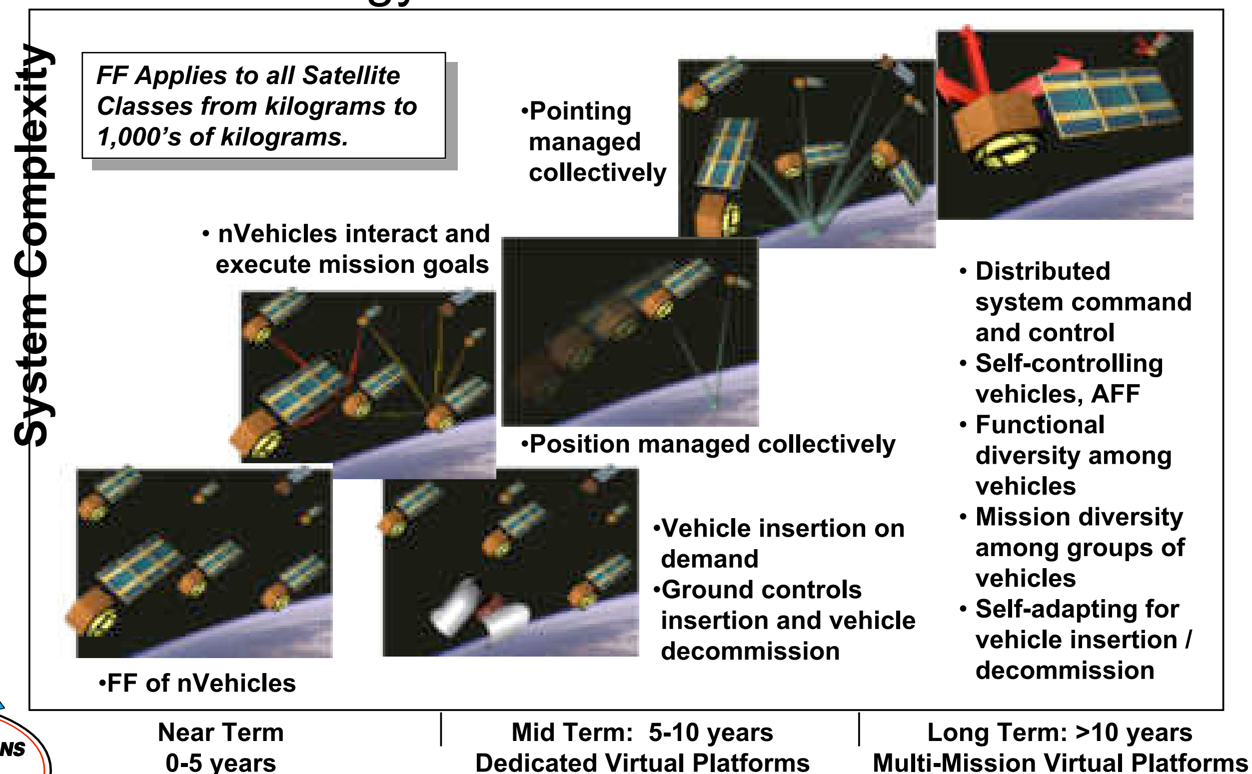
A, B, C are roadmaps in subsequent Tables

- *Missions (provides range and mid-term data points)*
  - *Current: Single Satellite Missions*
  - *Leonardo: Leonardo 2015 and Beyond*
  - *Advanced: Other Planned Formation Flying missions*
- *NASA Technology Readiness Levels (TRL)*

Mission Areas and Critical Technologies for Formation Flying (FF)

- *Autonomy for Distributed Systems; Distributed Remote Agent (A)*
- *Command, Guidance, Navigation, and Control of Distributed Space Platforms (A)*
- *Distrib. System Fault Tolerance (A)*
- *Design and Modeling of Distributed Architectures (A)*
- *Satellite Communications (B)*
  - *Intra-Spacecraft Links*
- *Distributed Computing (C)*
- *Nano/Micro-Propulsion (C)*
- *Power Collection & Distribution (C)*
- *Avionics (C)*

FF Technology Evolution



A. Mission Ops

B. Cluster Communications

C. Spacecraft Infrastructure

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Formation Flying Representative Missions

Mission	Launch Year	Status	No.Sats.	Orbit	Shape Control	Coordination Level	Navigational Accuracy	Connectivity	Est. NavComm DataRate (kbps)
EO-1 / LS-7	<2000	Flying	2	LEO	Ground	Collaborative	Loose	Direct	0
Cluster2	<2000	Flying	4	LEO	Passive	Collaborative	Loose	Direct	10
Orbital Express	2005	ph2 (phC/D)	2 - 4	LEO	Active	Collaborative	Spread	Direct	10
Starlight	2005	phB	2	helio	Active	Symbiotic	Tight	Direct	100
MMS	2008	formulation	4 - 5	HEO	Passive	Symbiotic	Tight	Broadcast	1000
LISA	2008	formulation	3 / 6	helio	Passive	Symbiotic	Complex	central ring	2000
GEC	2009	formulation	4 - 6	HEO	Passive	Collaborative	Loose	Direct	10
MagnetoConst	2011	formulation	50 - 100 (60)	HEO	Passive	Collaborative	Spread	String	5
TPF	2011	study	4 - 6 (5)	helio	Active	Symbiotic	Complex	Star	2000
Leonardo(BRDF)	2015	formulation	6	LEO	Passive	Symbiotic	Loose	Broadcast	50
Constellation-X	2015	technology	4	L2	Passive	Symbiotic	Tight	Broadcast	2000
SISP	2015	formulation	9 - 32	L2	Passive	Symbiotic	Complex	Broadcast	10000
RadBeltMapper	2015	formulation	100	mixed	Passive	Collaborative	Spread	Broadcast	5
GlobalPrecip (GPM)	unk	formulation	3 - 9	LEO	Passive	Collaborative	Loose	Broadcast	50
Tandem SAR	unk	formulation	2 - 5	LEO	Active	Symbiotic	Tight	Direct	100
RadioOccGPS(ATOMS)	unk	formulation	6 - 100	MEO	Passive	Collaborative	Loose	Broadcast	10

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Preview of Technology Assessment Results

Technology Areas			State of the Art			
			Available (7-9)	Qualifiable (4-6)	Develop (1-3)	Comments
A	Mission Operations					
		Guidance/Operations			*	Coordinated & Autonomous Operations {science & payloads}
		Navigation	x	x		
		Control	x	x		
		FDIR	x		*	Autonomous Reconfiguration of Cluster
B	Intra-Cluster Communications					
		Navigation	x	x	*	Proximity Networks; Expandable Networks
		Science		x	*	Node Control and Configuration; Security
C	Spacecraft Infrastructure					
		DataBus			*	IP-enabled Spacecraft
		Distributed Computing		x	*	Hetergenous Links; Realtime Reconfigurable Architecture
		Servers			x	Not a near term requirement

Key:
x - Being Developed
X - Needs Acceleration

Development in These Key Technologies Supports FF in a SensorWeb Architecture

Technology Presentation Roadmap Area (A)

Technology Area #A - Mission Operations <<

- (A.1) Guidance / Operations
- (A.2) Navigation (Orbital Control Systems)
- (A.3) Control (Attitude Control Systems)
- (A.4) Fault Detection Isolation and Recovery (FDIR)
- (A.5) Distributed System Autonomy

Technology Area #B Intra-Cluster Communications

- (B.1) Navigation & Operations
- (B.2) Science

Technology Area #C - Spacecraft Infrastructure

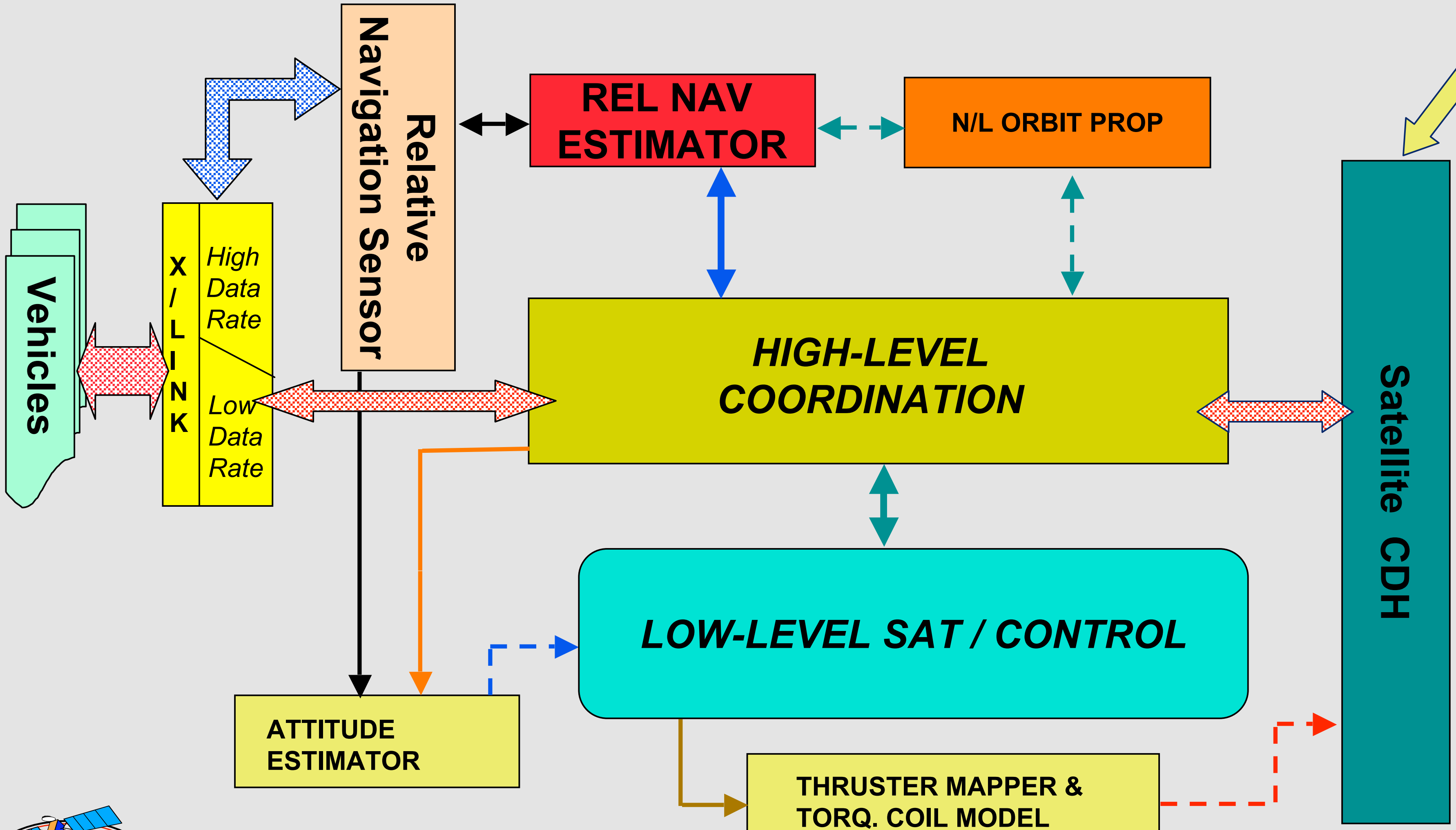
- (C.1) Data Bus (including Router)
- (C.2) Distributed Computing
- (C.3) Data Servers

(A.1) Guidance / Operations

Functions

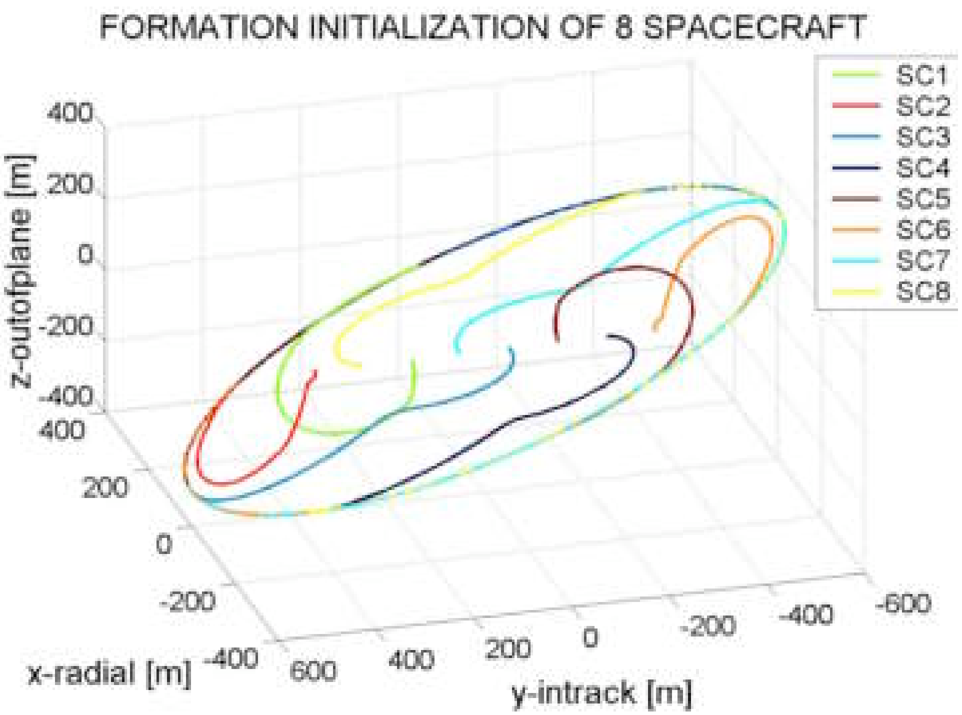
- Deployment
- Initialization and Checkout
- Calibration
- Operations
  - Formation Operations
  - Science Operations
  - Resource Scheduling

FF Control Architecture - Orion Example (SU)



High-level Coordination

- **_Coordinator performs:_**
  - **_–time division based coordination_**
  - **_–experiment control mode switching_**
  - **_–fuel optimal initial plan execution_**
  - **_–control to desired accuracy bounds_**
- **_Results impact fuel usage, mission lifetime, and pointing performance_**
- **_Coordinator decisions are very complex for large fleets_**
  - **_–But can distribute the coordination computation_**

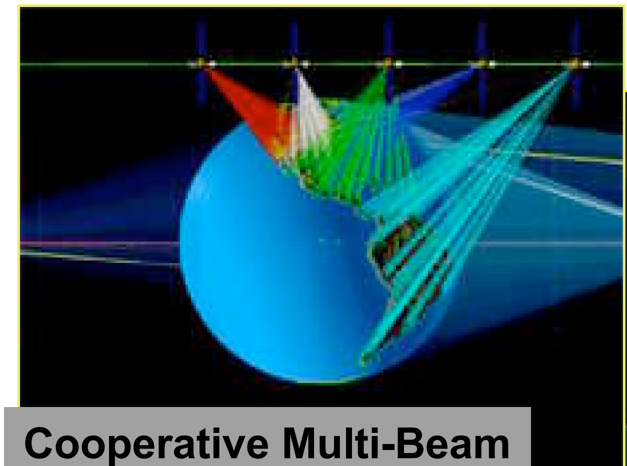


- **_Example: both local/central calculations used to determine final locations of 8 vehicles on a passive aperture_**

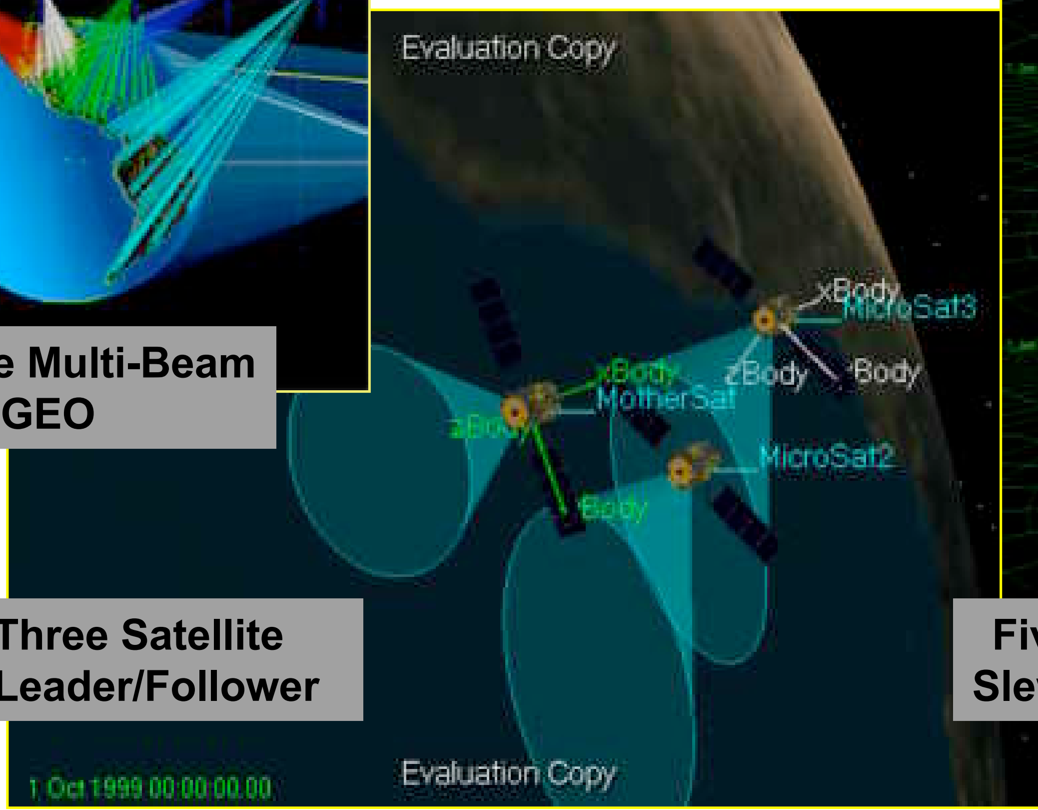
Attitude Command Generator

Objectives:

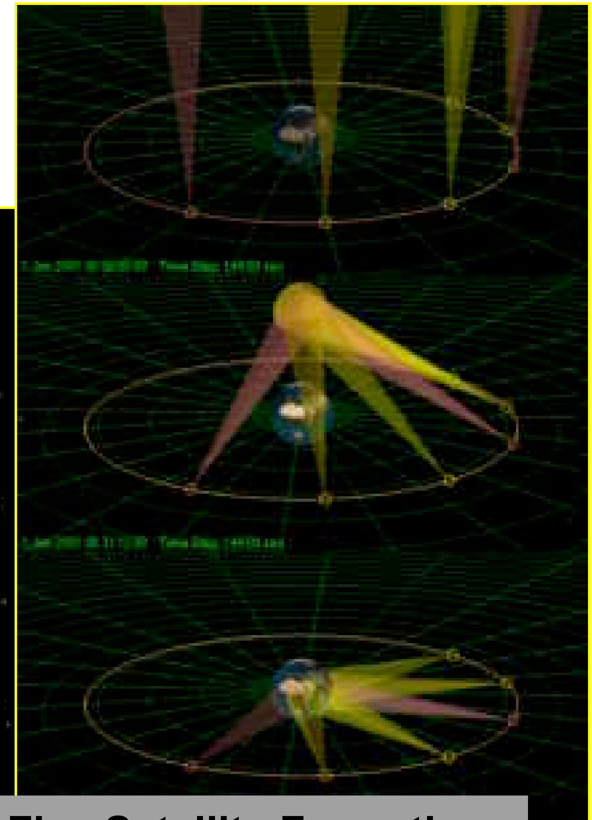
- ***Formation-Flying Satellites Able to Attitude-Maneuver to Any Target***
- ***Precision Cluster Pointing***
- ***Ground Targets and Star Targets***



Cooperative Multi-Beam Pointing at GEO



Three Satellite Leader/Follower



Five Satellite Formation Slewing to Ground Target

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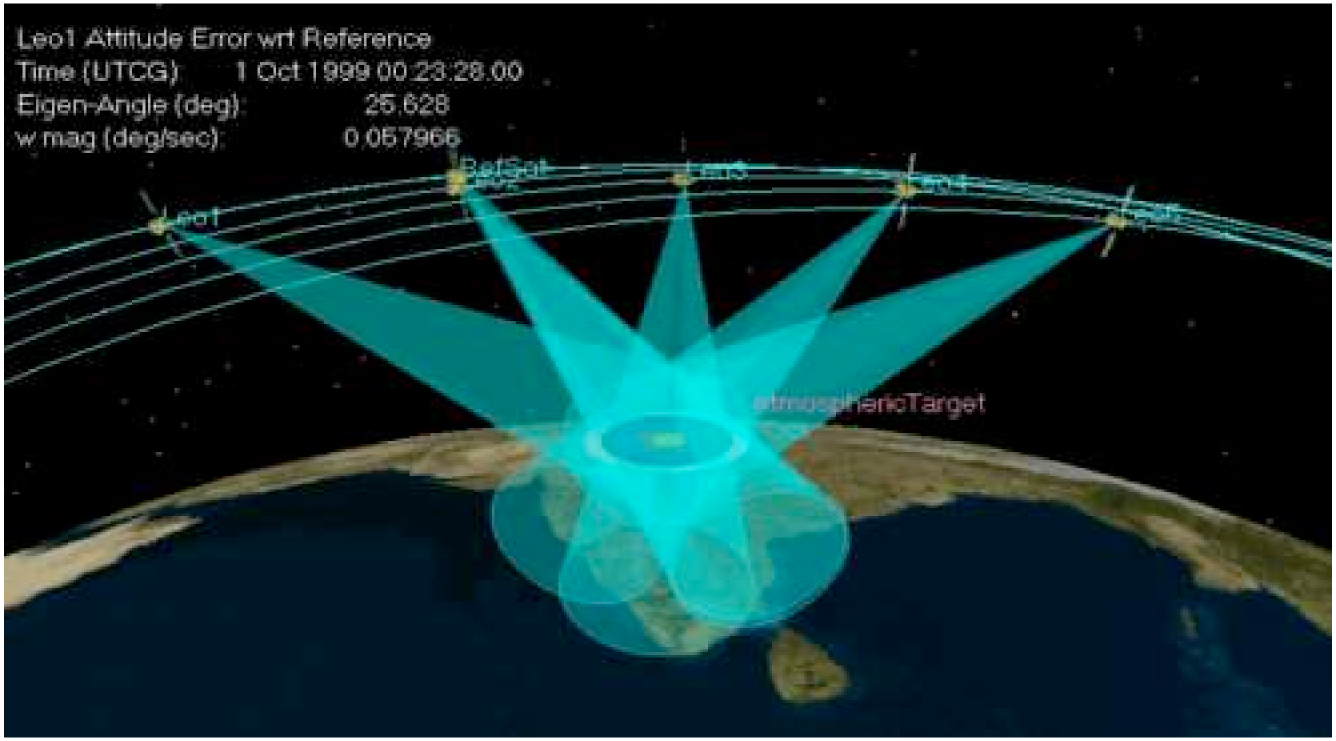
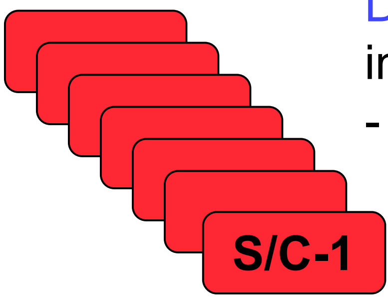
Guidance / Operations Technology
Leonardo Mission Simulation

- ***Simulation example; event of opportunity***

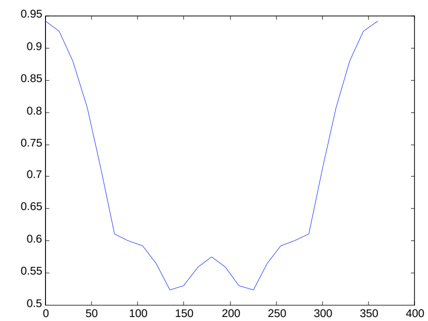


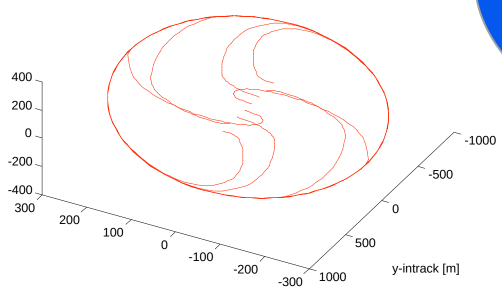
- ***Includes: autonomous science pointing command, autonomous attitude command generation, and resources allocations***

Resource Allocation



Distributed planning and bidding based on individual characteristics (actuation & computation)
- _V map vs Aperture location





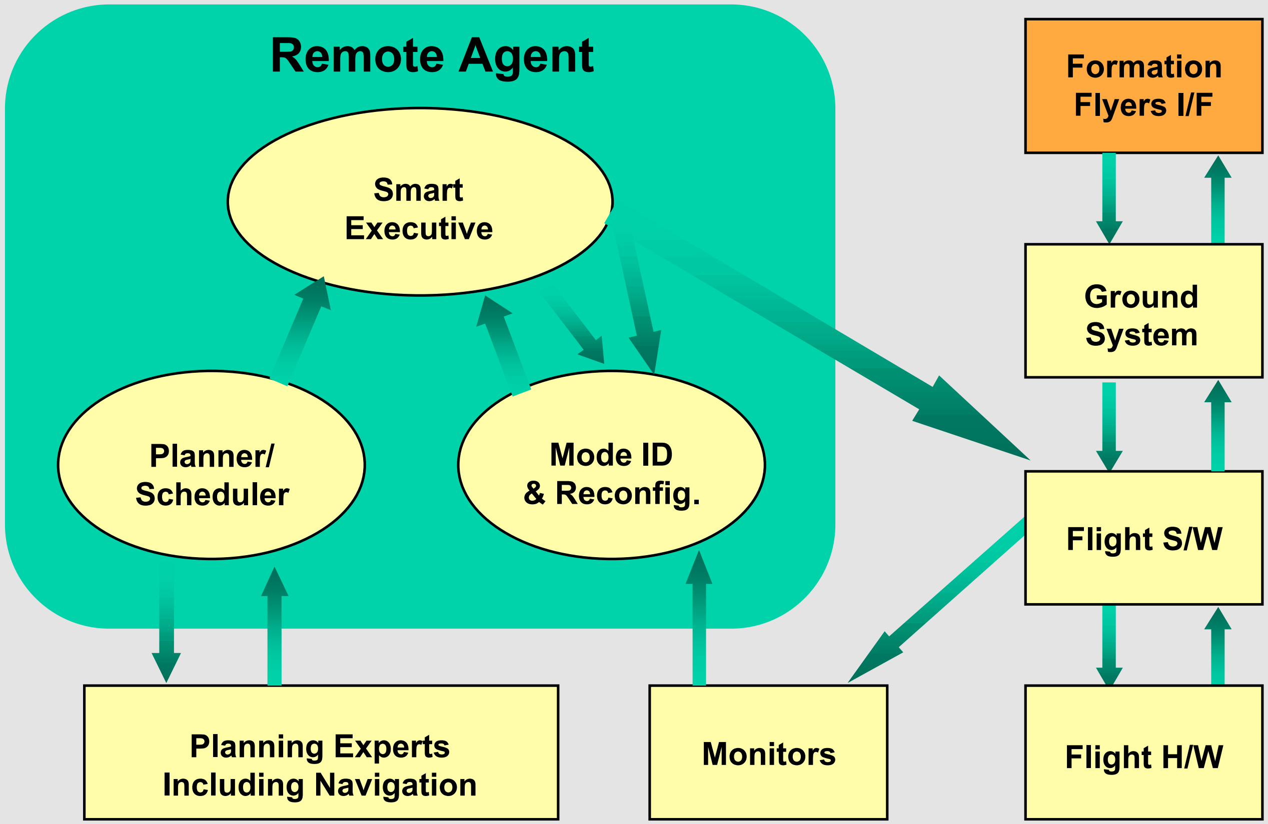
COORDINATOR

Mean Formation Elements & Optimal Aperture Characteristics

e_{mf} a_{mf} P_{mf} q_{mf}

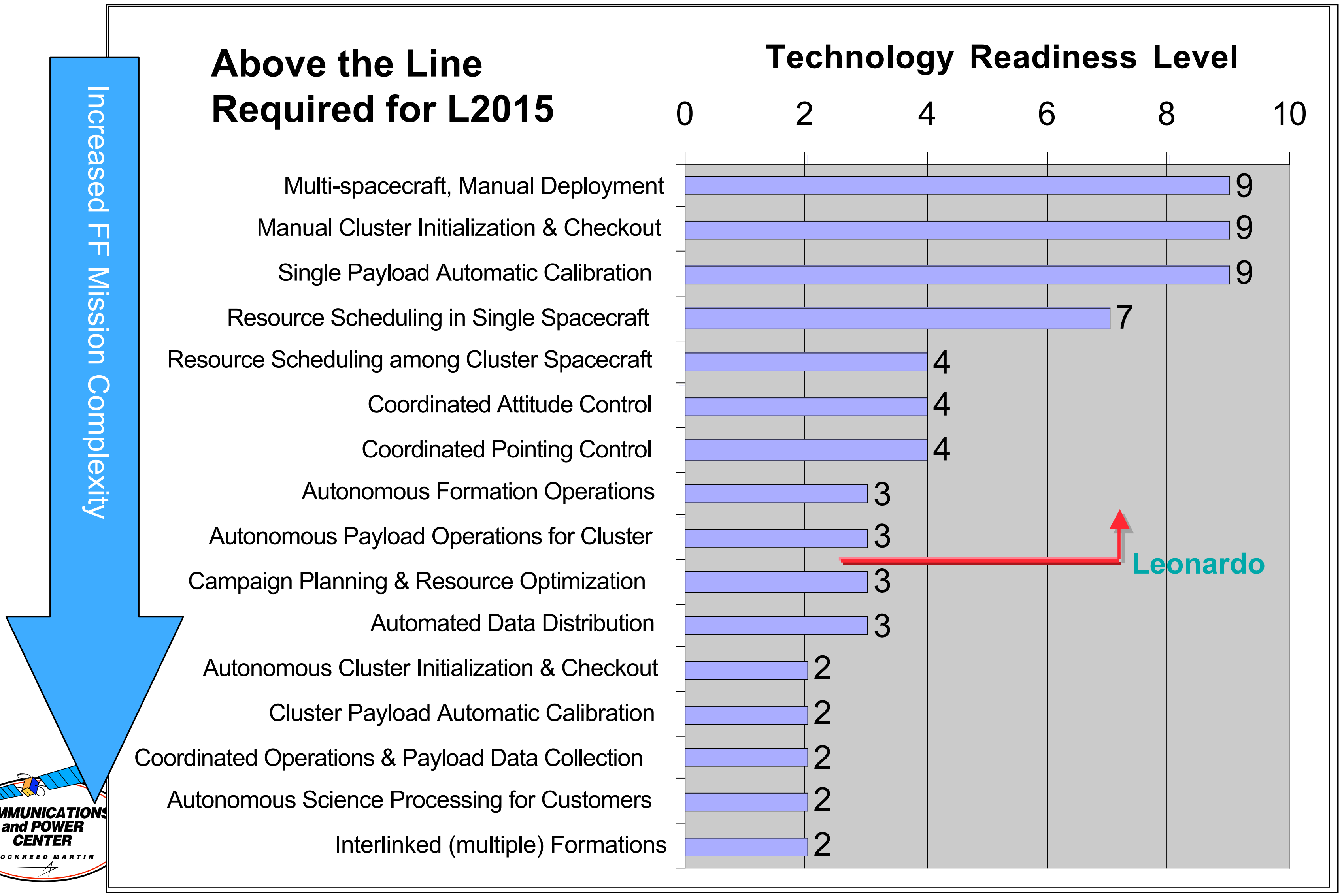
Complex selection criteria includes:
- collision avoidance
- logical statements / constraints
- fault processing

Distributed RA with FF Autonomy



Ames Remote Agent (RA) first on-orbit demonstration on DS-1, ‘98

(A.1) Guidance / Operations



(A.2) Navigation (Orbital Control Systems)

Functions

(A.2.1) Formation Control Algorithms

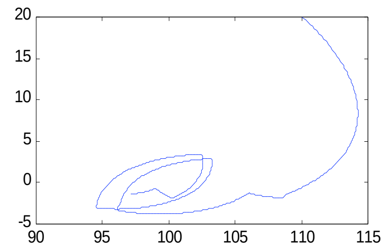
(A.2.2) Relative Navigation Sensors

(A.2.3) Navigation Communications
(see Technology Area #B)

Component Technologies can be Qualified;
The Issue is System Integration

Low-Level Satellite Control

- **Basic Regulators**
  - –LQG (centralized / decentralized)
  - –Gain scheduled for various experimental modes
- **Trajectory tracking**
  - –Guide vehicles to within desired relative error boxes
- **Fuel/time optimized phase-plane controllers designed for deep space applications**
- **LEO example:**
  - –shows switch to low-level control as spacecraft enters desired error box



GN&C
On-Board Processing Requirements

Approach:

Investigate the computational processing for one-sat in the formation during the transition from Deployment to Maneuver phase

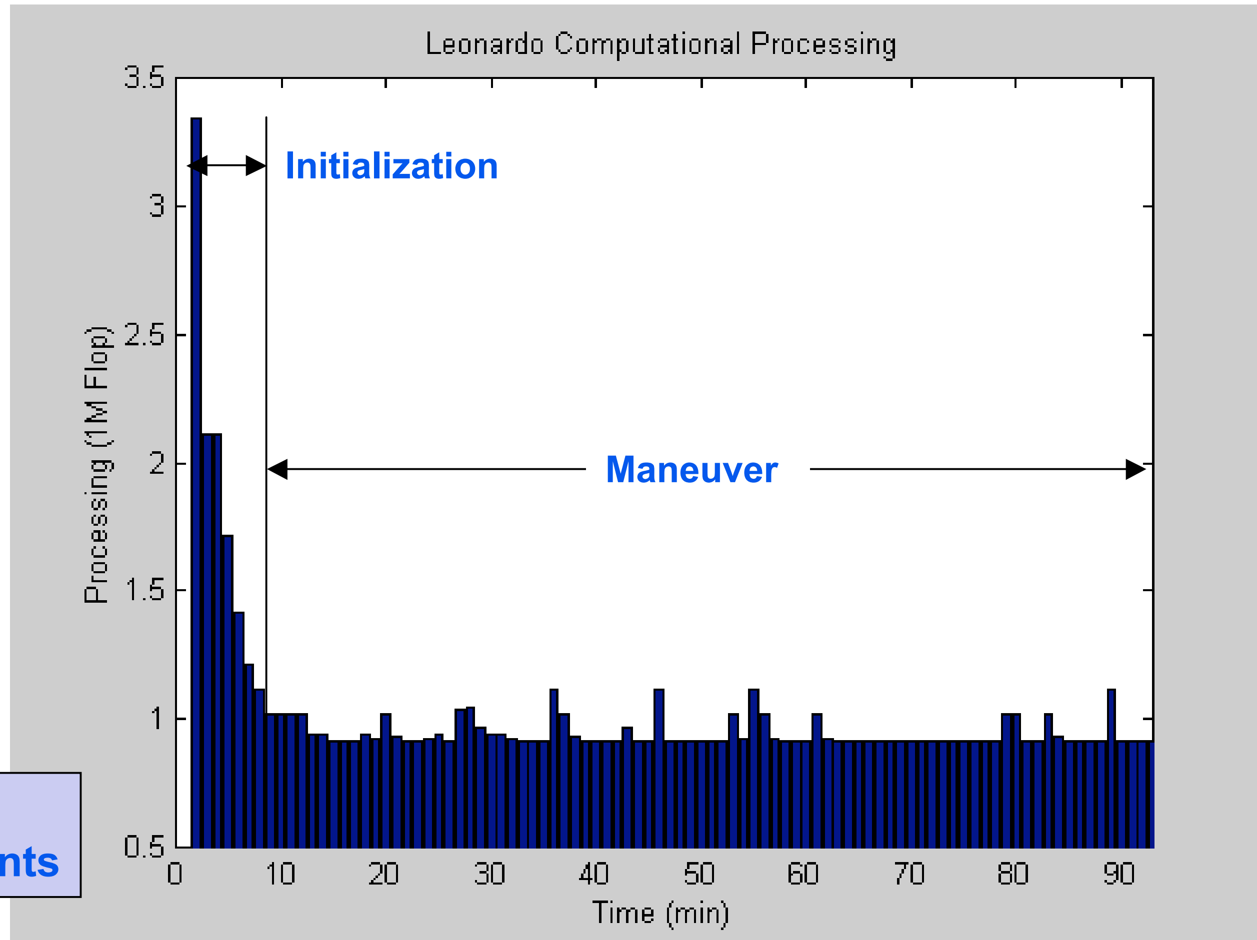
Key Parameters:

Orbit altitude, *circular 400Km, near- equatorial*

Number of Satellites*, 6-sats; Graph results for 1-sat only*

Control sample rate*, 60 seconds*

Sim. duration*, one orbit, 93 min*



Moderate Navigation Processing Requirements

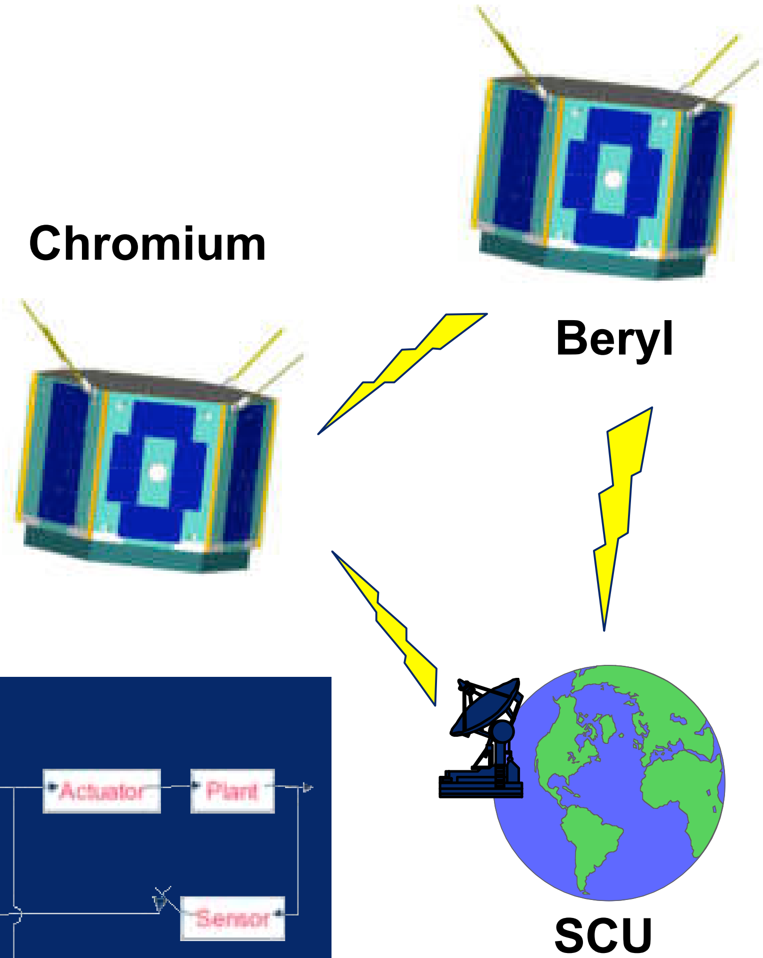
Decentralized Control for Multiple Spacecraft Formations

Objectives:

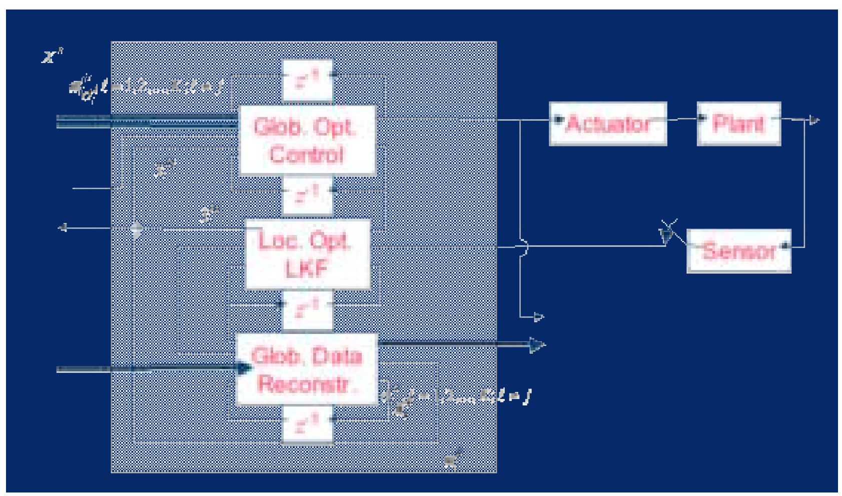
- ***Mitigate Risk Associated With Centralized Formations***
- ***Develop, Evaluate,and Flight-test the Decentralized Control Algorithm***

Accomplishments:

- ***Modeled Both Algorithms for a 3-satellite Distributed Formation***
- ***EMERALD Formation Flying Microsatellites ("Chromium" and "Beryl") to Evaluate Decentralized Control***

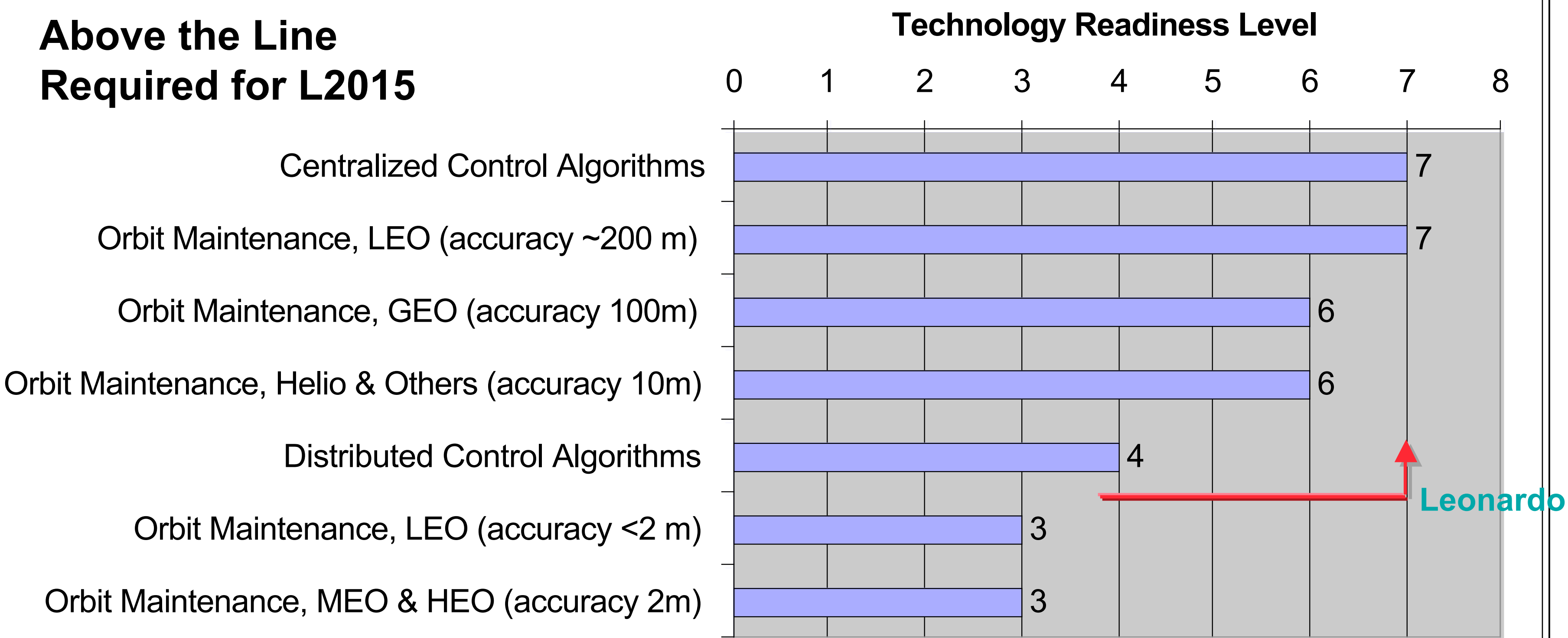


Santa Clara
NASA / GSFC
LM / ATC



(A.2.1) Formation Control Algorithms

Above the Line
Required for L2015



(A.2.2) Relative Navigation Sensors

- ***Distributed Command and Control: Sensing Options***
  - *GPS-derived RF systems for relative position and attitude determination in formation.*
  - *Navigation data exchanged via intra-cluster communication channel*
  - *Formation sensing augmentation by laser metrology; multiloop systems*

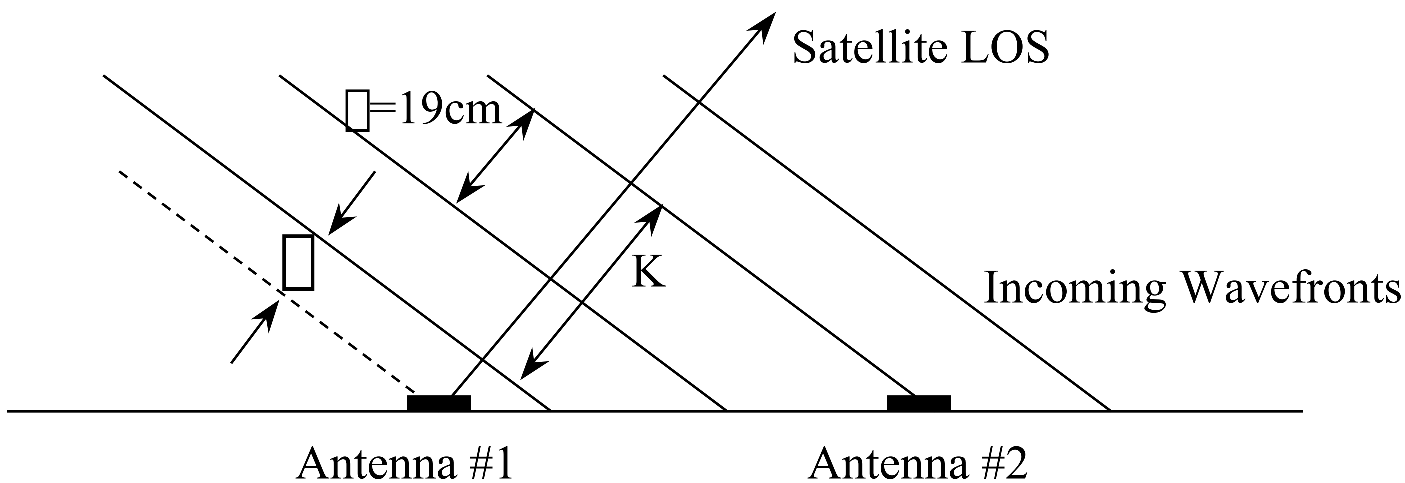
(A.2.2) Relative Navigation Sensors

System Type				
Name	Classification	**Capabilities (Range and Accuracy)**		**Technical Maturity**
		Linear Positioning		
		Position/Relative Distance	Velocity	
GPS Derived	**Active**			
Differential GPS	Code Divisible Multiple Access	Absolute position below 11,000 nm with 2 m accuracy	to within 5 cm/s	6
Carrier Phase GPS	Code Divisible Multiple Access	Absolute position below 11,000 nm with cm accuracy	yes (Doppler shift)	5
Local broadcasting with CP GPS	Code Divisible Multiple Access	absolute and relative positioning with cm accuracy	yes (Doppler shift)	5
LASER	**Active**			
Interferometer (phase measurement)	Interferometry	0.3 to >100 m with 1.5 mm accuracy	no	6
Interferometer (phase measurement)	Interferometry	3 to >100 m with 2 ppm accuracy (nm accuracy possible)	no	6
LIDAR	Time of Flight			
""	Time of Flight	range up to 10km	accuracy <0.5 m/s	5
""	""			
Mars polar Lander LIDAR	Time of Flight	range up to 750 m with 5 m resolution	no	7
Doppler velocimeter	Doppler Measurement	no	-0.2 to 2 m/s to within 0.4 cm/s	6
RF	**Active**			
RADAR (Ka band)	Time of Flight	range up to 1km with .15 cm accuracy/sample	0.45 m/s - 134 m/s to within 4.5 cm/s	7
Time modulated Ultra-Wideband(PPM)	Code Divisible Multiple Access	range up to 900 m with 3 cm accuracy	no	4
""	""	range up to 60 m with 1.3 cm accuracy	no	3
Visual				
Optical Flow	Passive	accuracy within 5% (much better now?)	yes	4
Spatial disparity with laser targeting	Active/Passive	yes	no	3
Magnetic				
Magnetometer	Passive	no	no	7
Pulsed DC	Time Division Multiple Access	5 m range with 1.5 cm accuracy	no	6
Low Frequency AC	Frequency Division Multiple Access	10 m range with 4 cm accuracy	no	6
AC Beacon Lattice	Code Division Multiple Access	5 m range with 5 cm (2 sd's) accuracy	no	3
Rejected Technologies				
Low frequency pulse (LORAN, 100kHz)		yes (low accuracy)	no	7
VHF Omni-directional Ranging (VOR)		yes (tenths of a mile)	no	7
Nondirectional Radio Beacon (NDB)		yes (low accuracy)	no	7

Selection depends on required range, accuracy, weight, volume, lifetime

GPS Measurement Observables

- *Code phase **measurements – L1-1575MHz, C/A & P, L2-1227MHz***
- ***1 MHz PRN code chipping rate, 1 msec epoch for C/A,** 30 m ranging accuracy*
- *Carrier phase **measurements – L1 wavelength 19cm,** 1 cm ranging accuracy*
- ***Doppler measurements***
- ***Accuracy vs. initialization/ambiguity tradeoff, no SA on carrier.***
- ***All GPS and GPS-like sensing systems have these basic observables***



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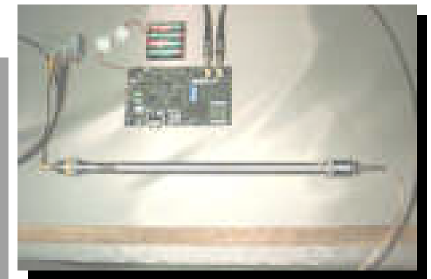
Different Methods of Using Observables

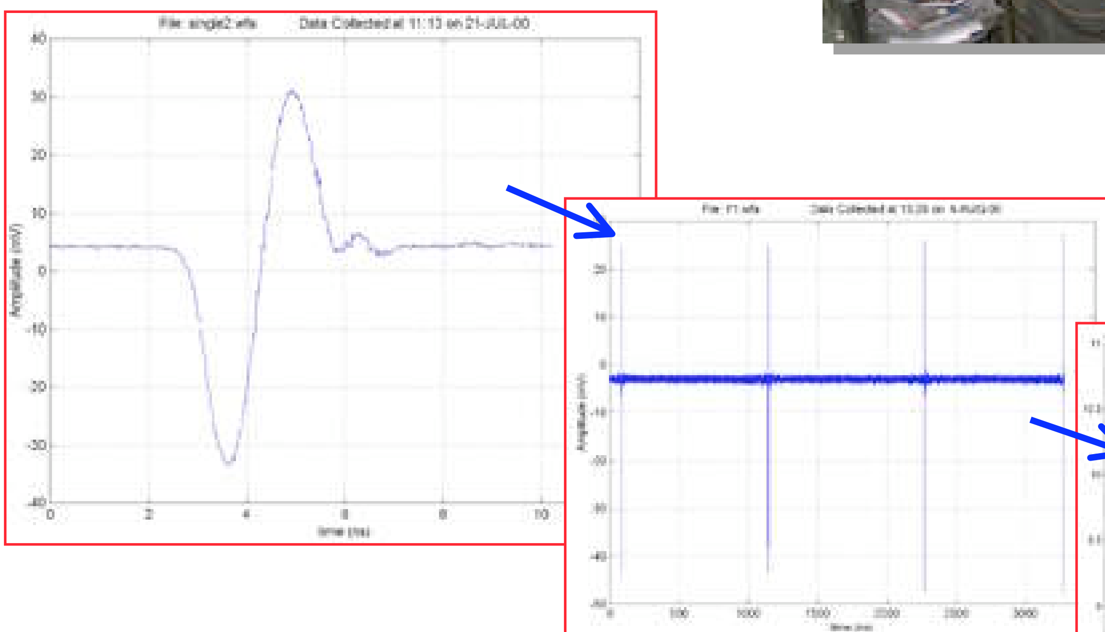
- ***Code Ranging – 4 transmitters req'd, accuracy 30 m, (100 m with SA)***
- ***Differential Code Ranging***
  - ***Local Area Augmentation(LAAS) => Aircraft landing***
  - ***Wide Area Augmentation(WAAS)=> Available to spacecraft, 1-2 m accuracy***
- ***Carrier Smoothed Code Ranging - precision OD***
- ***Differential Carrier Phase positioning - Real-time Kinematics (RTK) to surveyors***

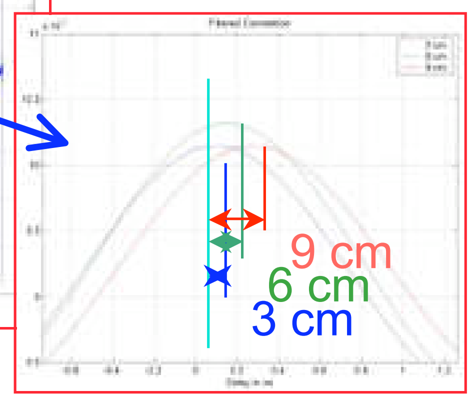
Relative Navigation for FF Missions

Ultra Wide Band; Comm & Position Determination



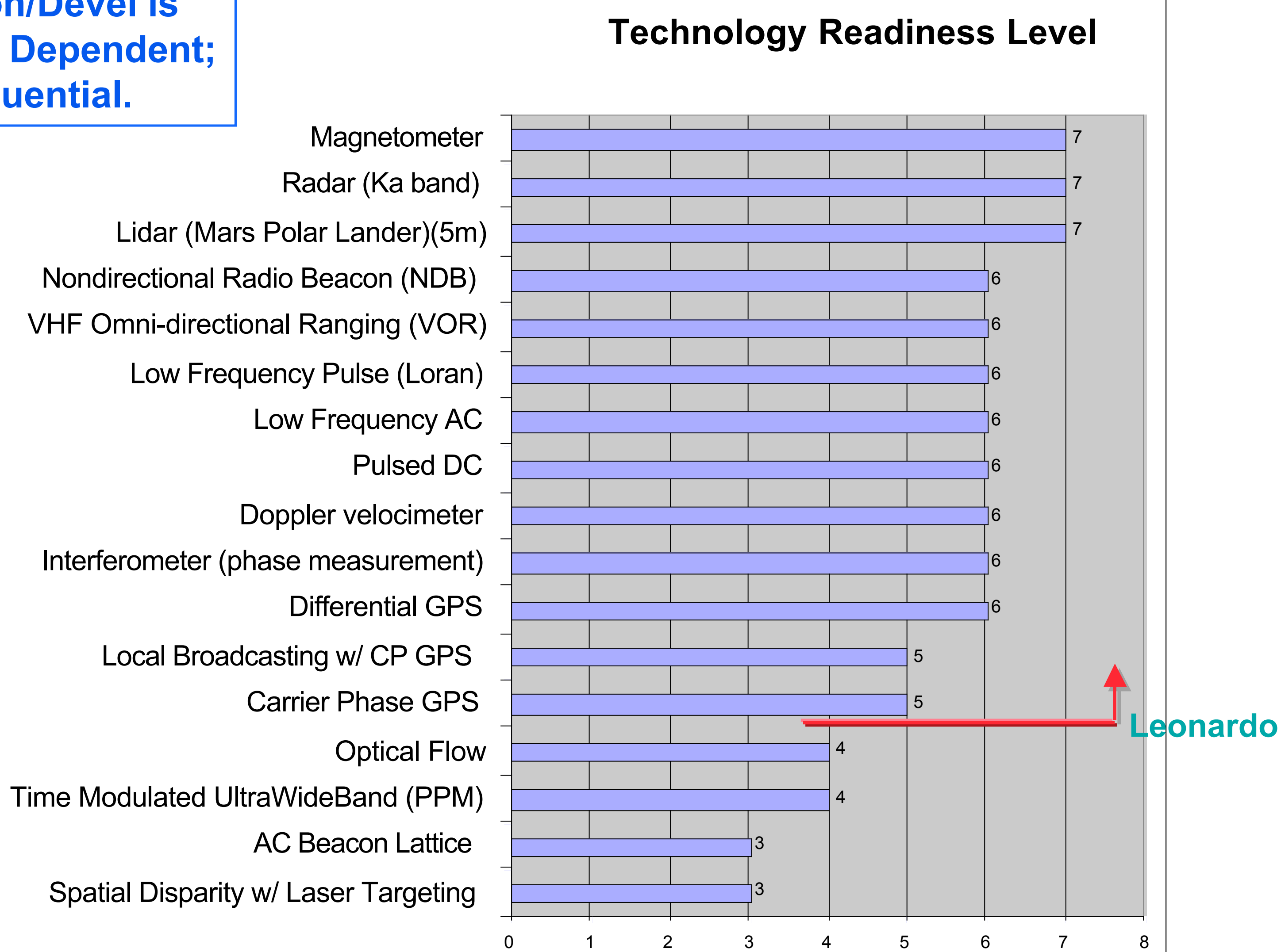
0.9 to 2.2 GHz Xmt/Rcv





(A.2.2) Relative Nav Sensors

Selection/Devel is Mission Dependent; Not Sequential.



(A.3) Formation Control

(Attitude Control Systems)

(A.3.1) Spacecraft Control Sensors

(A.3.2) Spacecraft Actuation

These Technologies are not Drivers for Leonardo 2015 (Performance Already Meets Requirements)

(A.4) Fault Detection Isolation and Recovery (FDIR)

Functions

- *Collision Avoidance*
- *Telemetry Processing*
- *Safing*
- *Reconfiguration / Fail Operational / Assured Data Delivery*

FDIR for Formation Functionality

- Formations inherently contain additional levels of composed functions whose operation needs to be assured
  - Safety
    - Collision
    - Availability of Navigation Data (Must still compute without complete data set)
    - Computing (cannot hang awaiting responses or metadata)
  - Operations
    - Continued delivery of sensed frame (integrated processing must be able to adjust parameters for incomplete apertures)
    - Assured delivery of science data (no single point transfer failure)
- Adding Formation FDIR places additional requirements on individual Spacecraft FDIR.
- Need to increase ability to fail operational rather than fail safe

FDIR Increased Platform Functionality

Integrated System Health Management

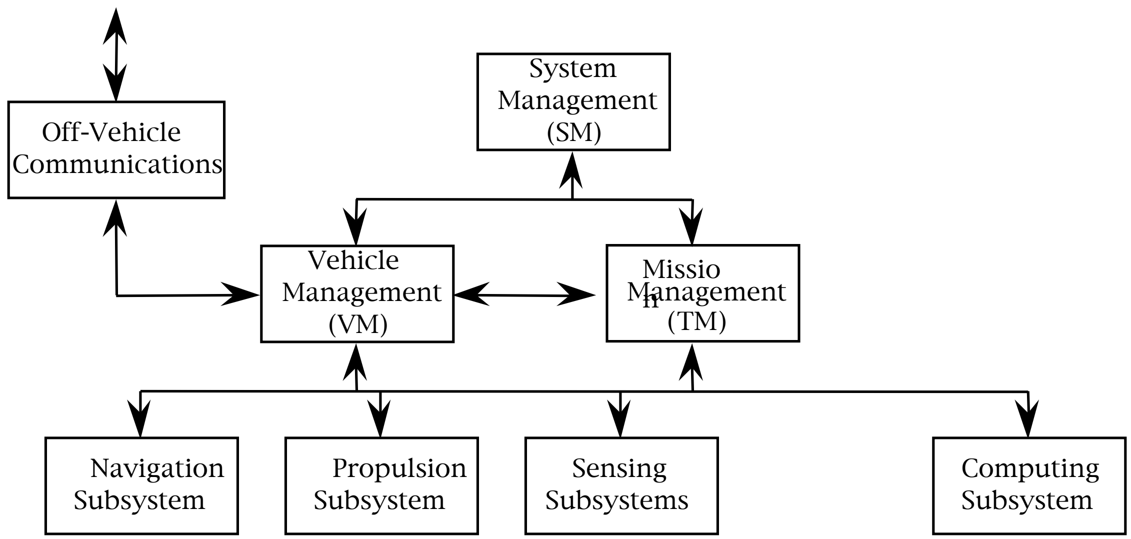


Figure 1
Integrated System Health Management Architecture

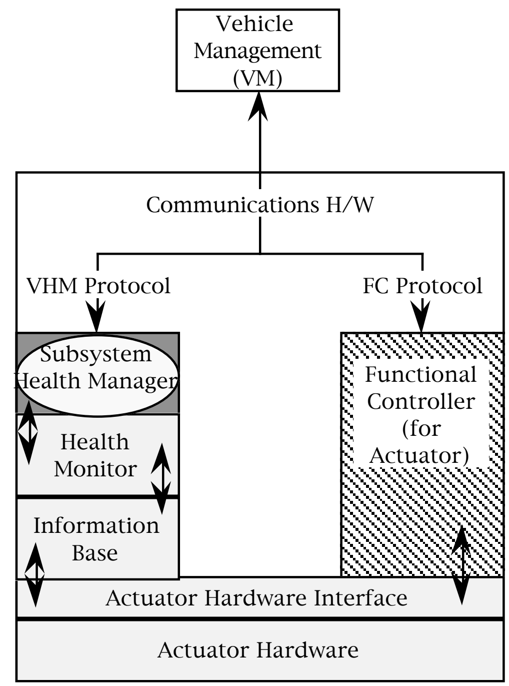
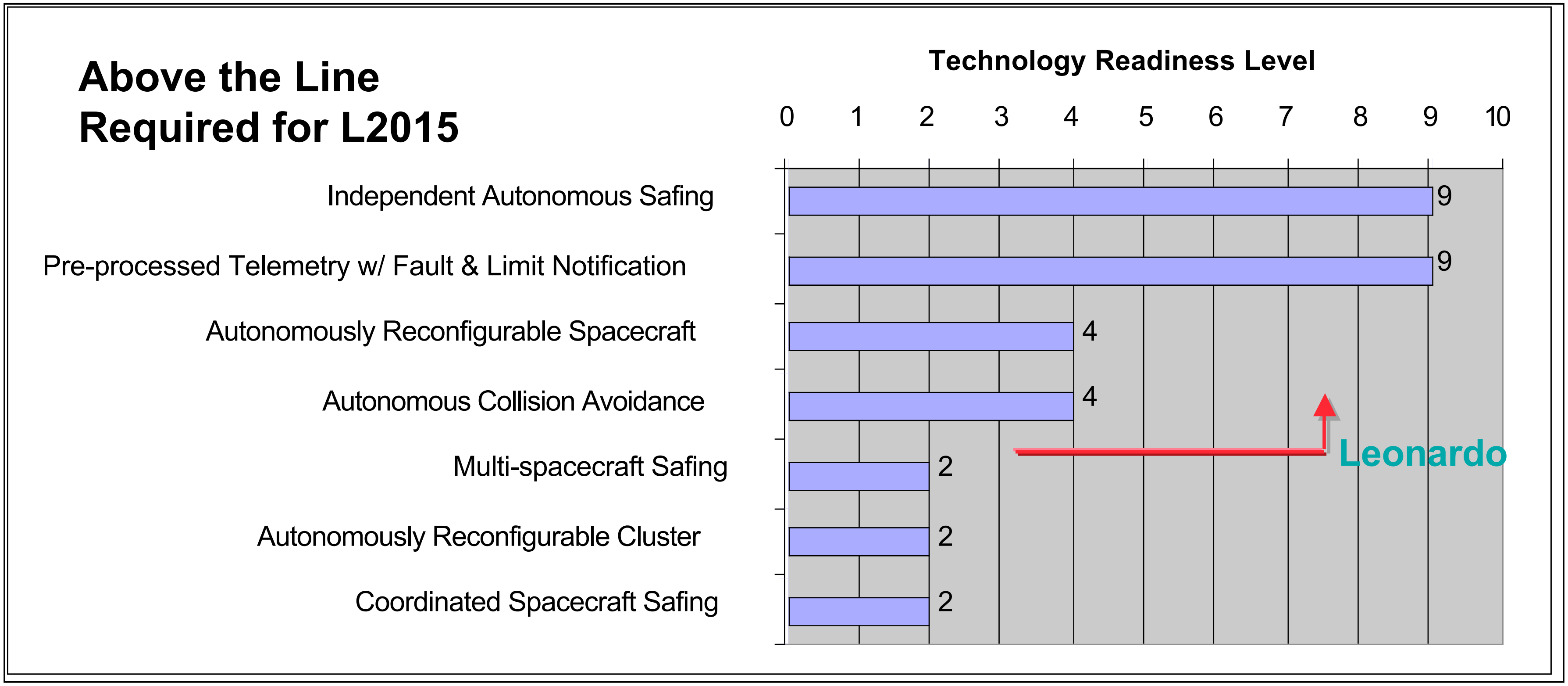


Figure 2
Typical Subsystem Architecture

Ref. "Integrated System Health Management (for Fleets of Autonomous Platforms)", Byler 1996.

(A.4) Fault Detection Isolation & Recovery (FDIR)



(A.5) Distributed System Autonomy

Functions

- *Separation Maintenance*
- *Mission Operations*
- *Failure Diagnosis and Self-Configuration*
- *Resource Allocation*
  - *Fuel Balancing*
  - *Sensor Management*
- *Maneuver Decision Making*

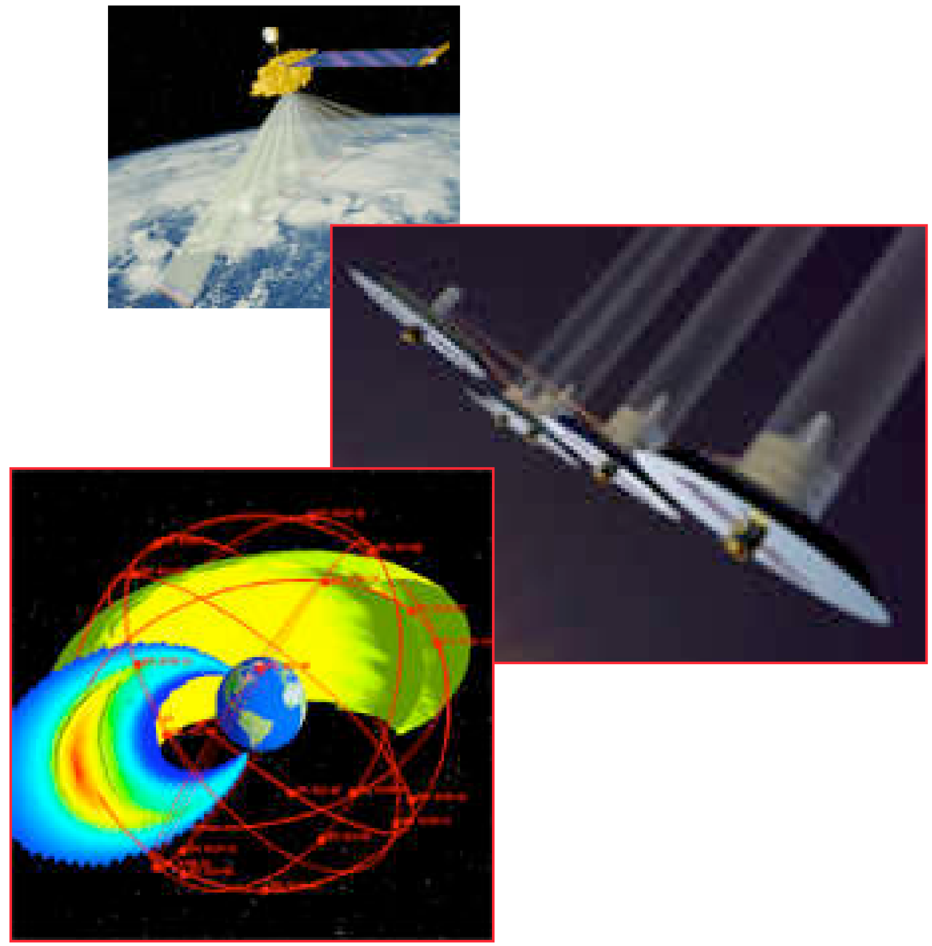
Future Space Missions Need Autonomy

Challenges

- More processing capability means more interesting science and greater system complexity
  - Distributed platforms
  - Resource allocation
  - Heterogeneous constituents
  - Coordinated mission ops
- Smart systems drive autonomy below the spacecraft level

Research Objectives

- Define suitable architectures that are sustainable as complexity grows
- Identify key technologies and processes



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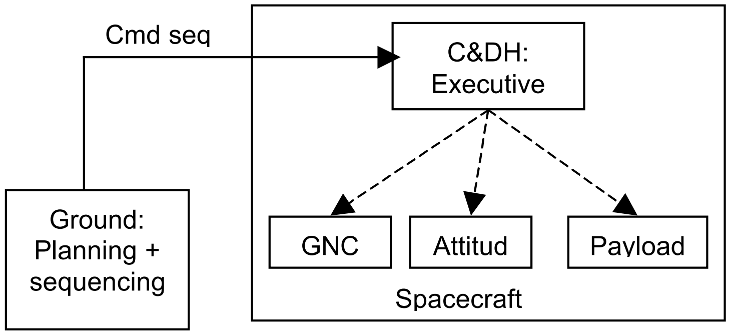
Research Approach

- *Develop comparable conceptual models for different autonomy implementation architectures for spacecraft domain:*
  - *Developed 5 models (with implementation options, e.g., centralized, distributed, hierarchical, peer, single & multi-entity)*
    - *(A) Decoupled command and control*
    - *(B) Platform Autonomy (PA)*
    - *(C) PA with Hierarchy*
    - *(D) Functional Subsystem Autonomy (FSA)*
    - *(E) Integrated FSA & PA*
- *Develop taxonomy for classifying/analyzing missions (requirements) from the autonomy perspective for cooperating*
  - *Sampling strategy identified as key parameter for classifying missions*
- *Identify and evaluate systems component technologies required for autonomous system architectures*
  - *e.g.: Decision Making & Control techniques, middleware*
- *Assess maturity of technologies in the context of the above framework*
  - *Evaluate Leonardo BDRF-2015 as test case using above framework*

Spacecraft Domain

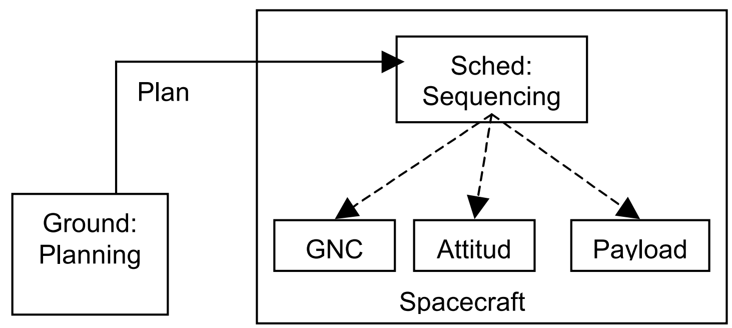
Architecture A



Ground based commanding and control for single or multiple spacecraft:

- ***Command sequence generated on ground and sent to spacecraft***
- ***Commands and sequencing for each platform are coordinated a priori to accomplish distributed system***
- ***Issues:***
  - ***Limited ability to respond to changing environment***
  - ***May be labor intensive, lie., costly***
- ***Example – Typical current spacecraft operations***

Architecture B



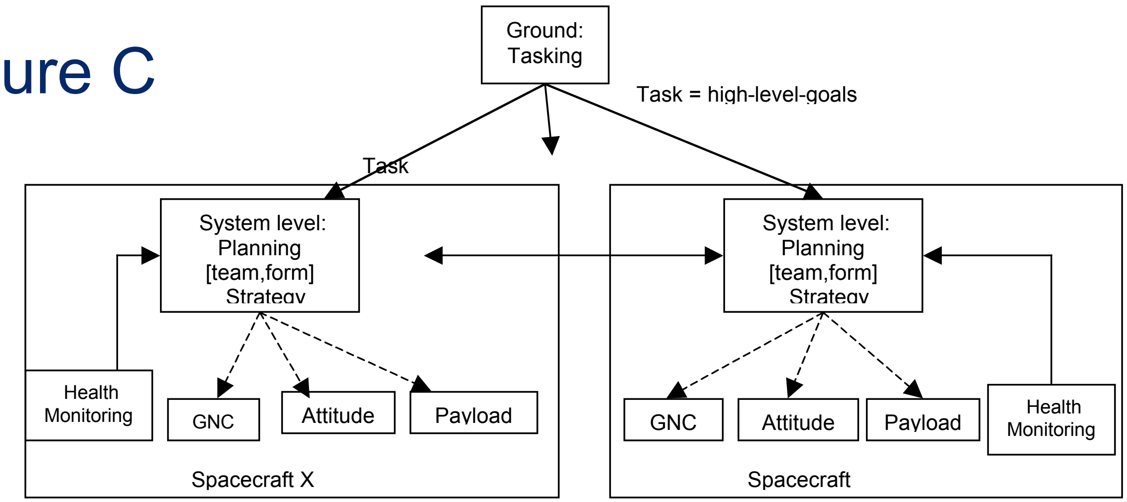
Platform autonomy for single or multiple spacecraft:

- ***High level plans generated on ground***
- ***Plans are decomposed into sequenced actions onboard platform***
- ***Plans are coordinated a priori to accomplish distributed system***
- ***Issues: Limited ability to respond to changing environment***
- ***Example – CASPER/ASPEM applied to Terra (EO-1) and DS-1***

Spacecraft Domain

Architecture C

Note:
The dotted connections Denote Control Flow



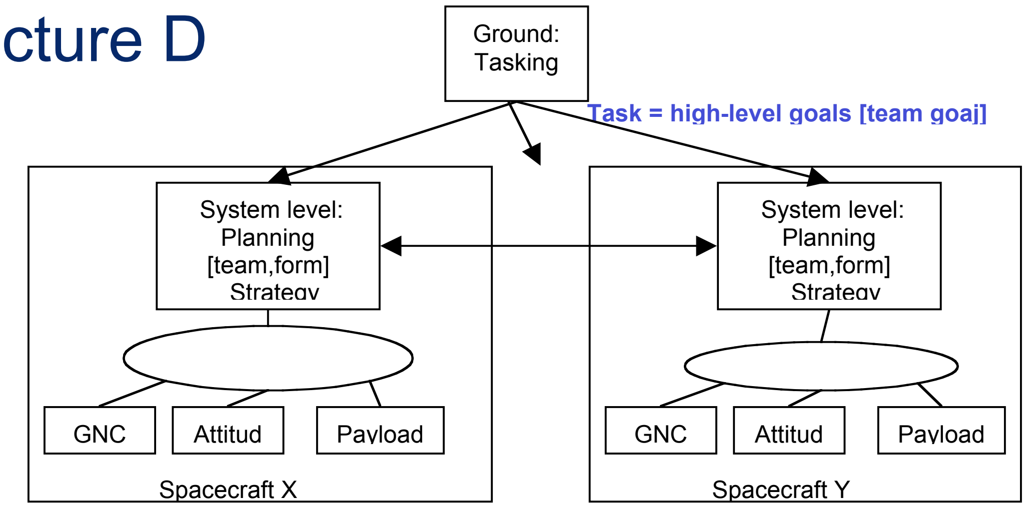
- **Centralized Platform Autonomy on-board (I.e. NO FSA)**
- **Decentralized (hierarchical or non-hierarchical) in Team [between the PA]**
- **Needs S/C cross-link**

System autonomy for multiple spacecraft

- ***High level plans (team objectives) generated on ground***
- ***Spacecraft has Autonomy in tasking, roles, tactics, sequencing***
  - ***Cooperation by the planners to decide on tasks based on Team-wide resources***
  - ***System has ability to respond to changing environmental conditions***
- ***Option1: Hierarchical control-based Decomposition of Platform Autonomy***
  - ***ICBAAT Approach – Active Market-based Cooperation Models [others to perform the task based on price/cost function]***
  - ***Passive Cooperation:: Based on Sharing State/goals/plan data – traditional planning/JPL***
- ***Option 2: Cooperative Planning and Execution: JPL Anthony Barrett***
- ***Issues: Middleware or Underlying (software) Framework (messaging, exchange, etc), Need for cross-links, Implementation with heterogeneous components***

Spacecraft Domain

Architecture D

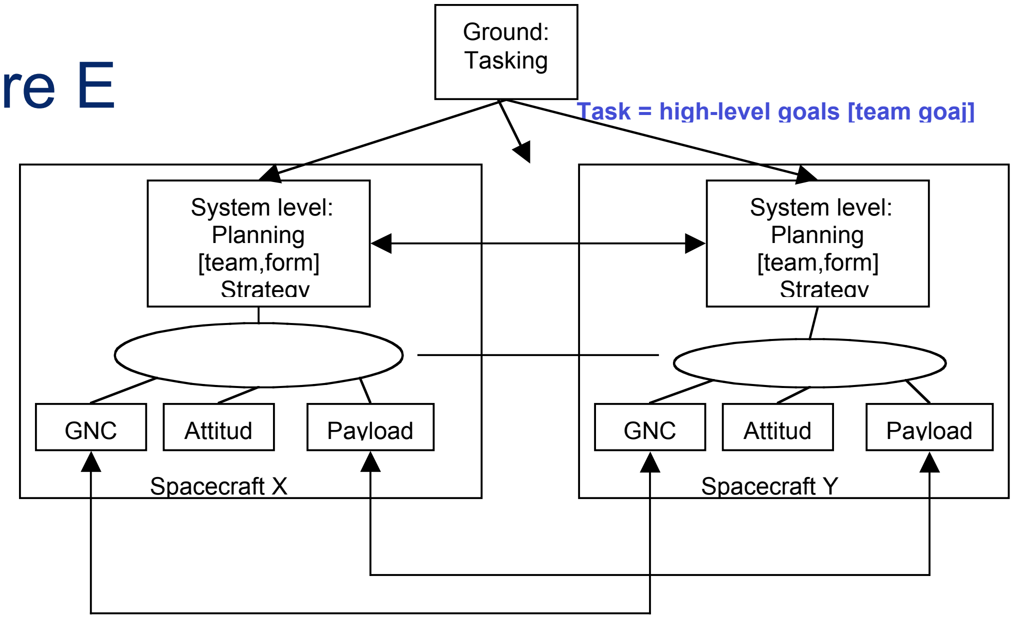


System autonomy for spacecraft with decentralized onboard autonomy high level plans (team objectives) generated on ground

- ***Spacecraft has autonomy in tasking, roles, tactics, sequencing***
  - ***Incremental autonomy enabling of individual subsystems***
  - ***Cooperation by the planners to decide on tasks based on Team-wide resources***
  - ***Improved flexibility to deal with changing environment***
- ***Issues: Middleware and communications framework on bus (messaging, data exchange), Implementation with heterogeneous components***

Spacecraft Domain

Architecture E



System autonomy for multiple spacecraft with close functional cooperation:

- ***High level plans (team objectives) generated on ground***
- ***Spacecraft has autonomy in tasking, roles, tactics, sequencing***
  - ***Incremental autonomy enabling of individual subsystems -***
  - ***Cooperation by the planners to decide on tasks based on Team-wide resources***
  - ***Improved flexibility to deal with changing environment***
  - ***Best ability to coordinate/manage system with heterogeneous components***
- ***Issues: Middleware or Underlying (software) Framework (messaging, exchange, etc). Need: cross-links, discovery mechanisms, Authentication, Network resource management***

Technologies Supporting Distributed Systems Autonomy

Decision Technology	Autonomy Domain	Comments
Fuzzy Logic	***Separation maintenance***	***Validated on EO-1 (TRL-7). Issue: How to ensure that the actions of the decision element get coordinated for global constraint::a)*** Implicit – via the model used
Planning	***Mission operations***	***Issue:: How to ensure that the actions of the decision element get coordinated for global constraint:: a)*** Explicit – share state – plans, decisions***.***
Model-based	***Failure diagnosis and self-configuration***	***Pros: Local recovery for subsystem health. Remote agent demonstrated DS-1.*** Issue: integrating and coordinating for re-tasking
Market-based	***Fuel-balancing,*** ***Sensor mgmt.,***	***Pros: distributed decision making – ensures that actions get coordinated to optimize***
Neural-net based	***Maneuver decision making,***	

Leonardo Assessment

Architecture C for L2015

- ***BRDF geometry oriented tasking and Formation control [Criticality: High]***
  - ***Decentralized: GPS enabled relative navigation coupled with control-box decision making and maneuvers [TRL: 5]***
    - ***Issue: Fuel Balancing***
    - ***Option: Dynamic Leader selection [TRL: 4]***
- ***Multi-platform BRDF Sensing [criticality: high]***
- ***Distributed Sensor control decision making and commanding [criticality: high]***
  - ***Centralized Sensor control decision making [TRL: 4]***
    - ***Dependent on the fusion strategy [co-locating the fusion node with the control node]***
    - ***Issue: a) Communicating state knowledge***
- ***Fusion of Sensor data (image registrations) for coherency [criticality: High]***
  - ***Centralized (collector-combiner approach)***
- ***Adaptive Sampling Strategy [criticality: medium]***
  - ***Rationale: Leonardo as an In-situ testbed for distributed FF earth-science missions must be able to shift to a stable sampling mode based on initial exploration***
  - ***In-situ coupling and coordination of Sensing, Processing and Flight***

Technology Area Presentation Roadmap (B)

Technology Area #A - Mission Operations

- (A.1) Guidance / Operations
- (A.2) Navigation (Orbital Control Systems)
- (A.3) Control (Attitude Control Systems)
- (A.4) Fault Detection Isolation and Recovery (FDIR)

Technology Area #B Intra-Cluster Communications <<

- (B.1) Navigation & Operations
- (B.2) Science

Technology Area #C - Spacecraft Infrastructure

- (C.1) Data Bus (including Router)
- (C.2) Distributed Computing
- (C.3) Data Servers

(B.1) Intra-Cluster Communications for Navigation and Operations

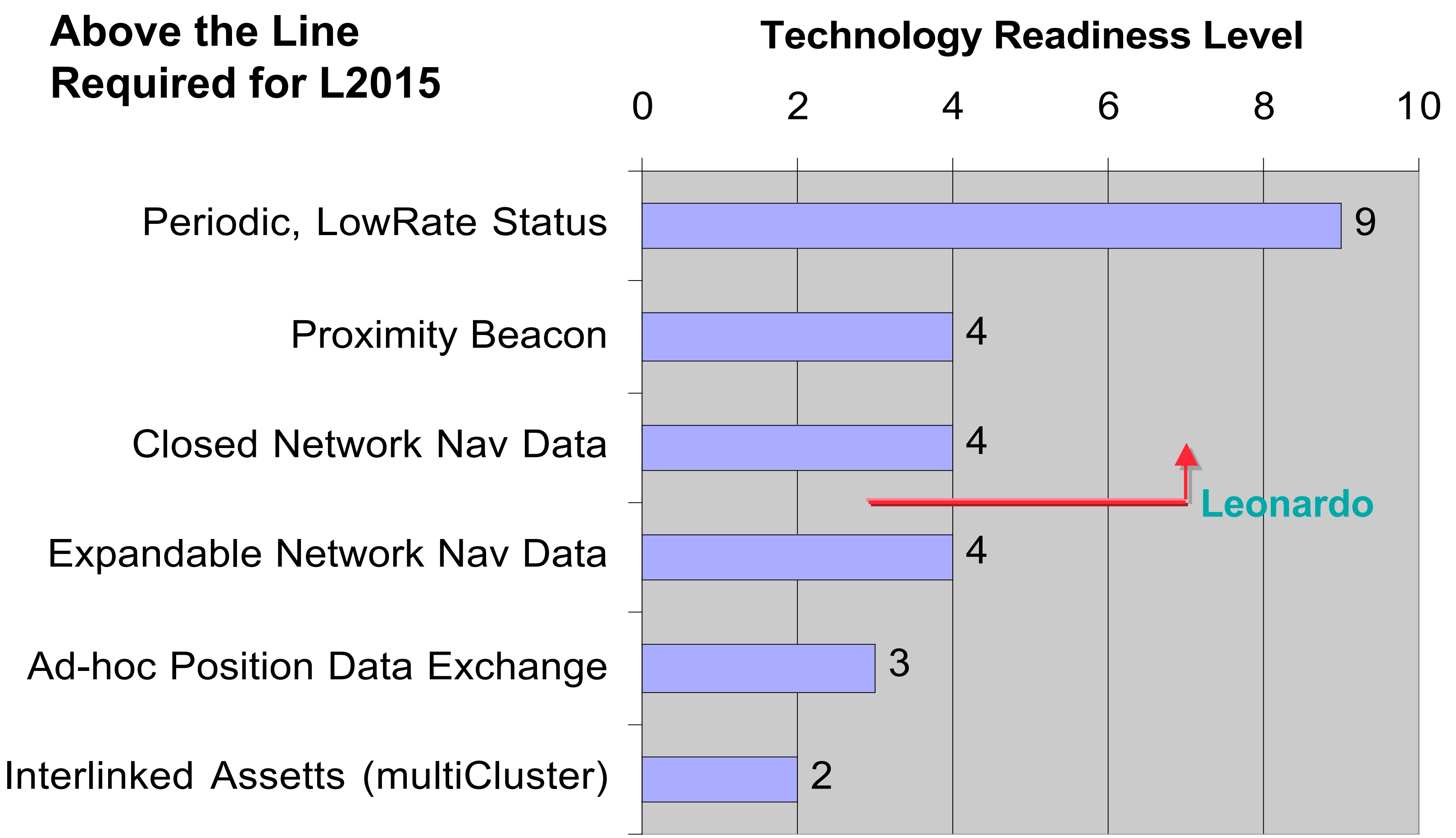
Functions

(B.1.1) Upper Level NavComm Functionality

(B.1.2) Comm-Based Relative Navigation Regime

(B.1.3) Navigation Transceiver Data Rates and Devices

(B.1.1) Upper Level NavComm Functionality



GN&C Update Rate for Precise Relative Position Control

Approach:

Investigate the update rate for a precision relative position control for two spacecraft

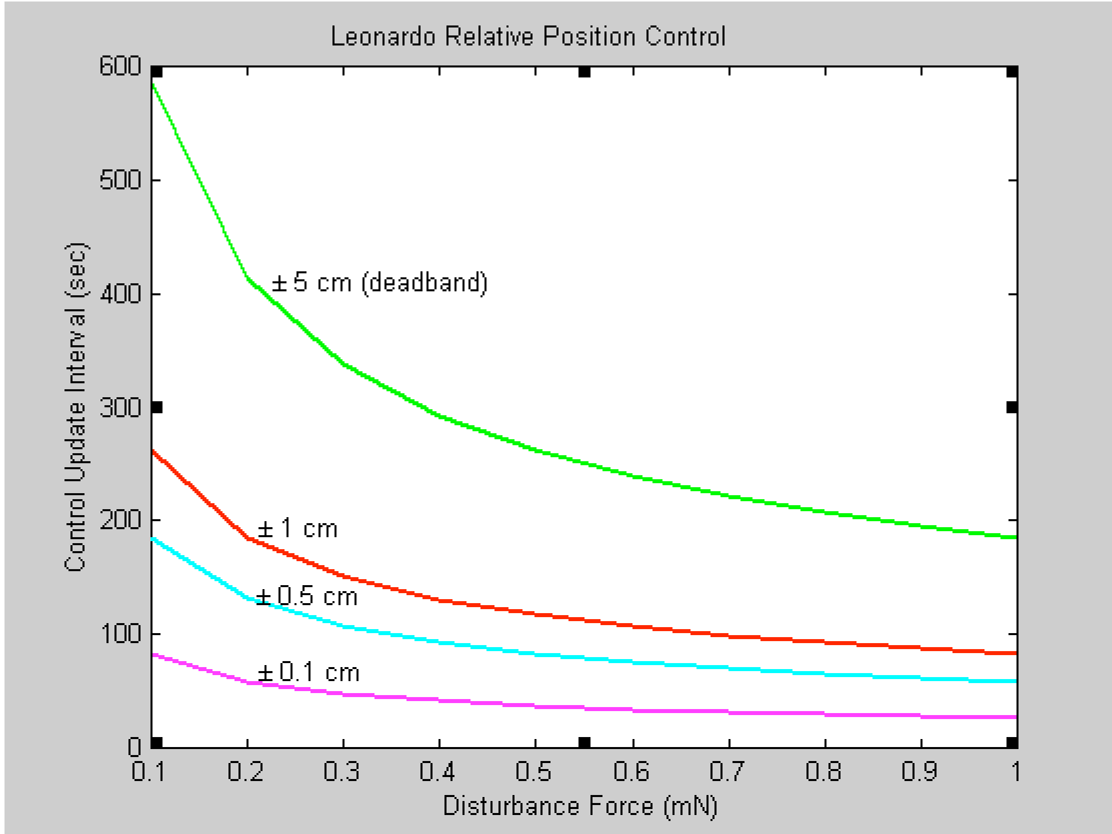
Key Parameters:

Orbit altitude, circular 400Km, near-equatorial

Disturbance force, modeled as a constant force of 0.1 to 1 mN

Position control, deadband varied for ± 0.1 cm to ± 5 cm

IBIT, i.e. 50e-6 based on 5mN thruster with minimum pulse of 10 ms



Moderate to Low Control Update Rate Requirements Gives Low Nav Communication Rate Requirements

(Ref. Starlight for attitude sensor and thruster performance)

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GN&C Decentralized Navigation Communications

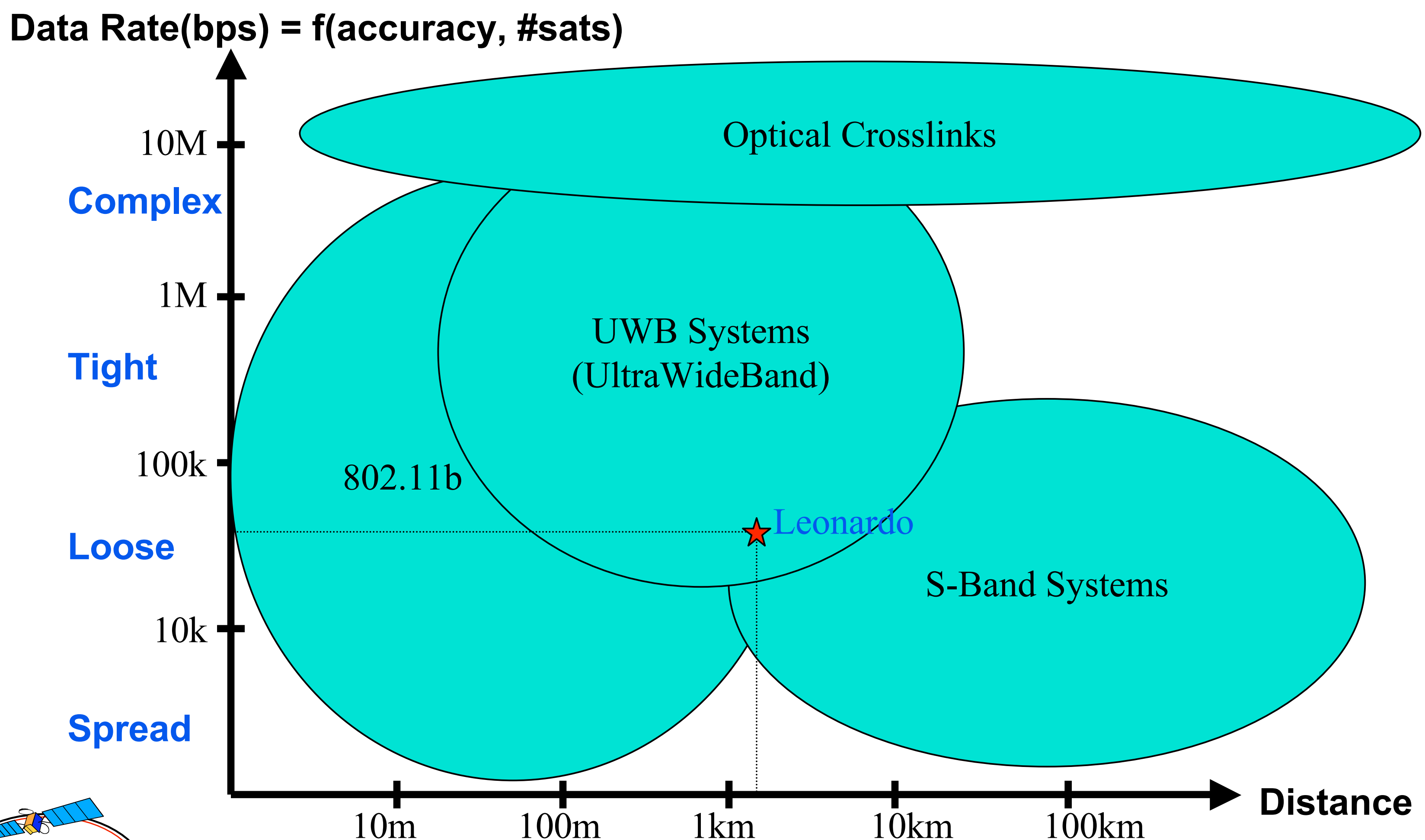
Range of Formation Flying "Performance Levels

Aspect/Attributes Needed for Formation Flying

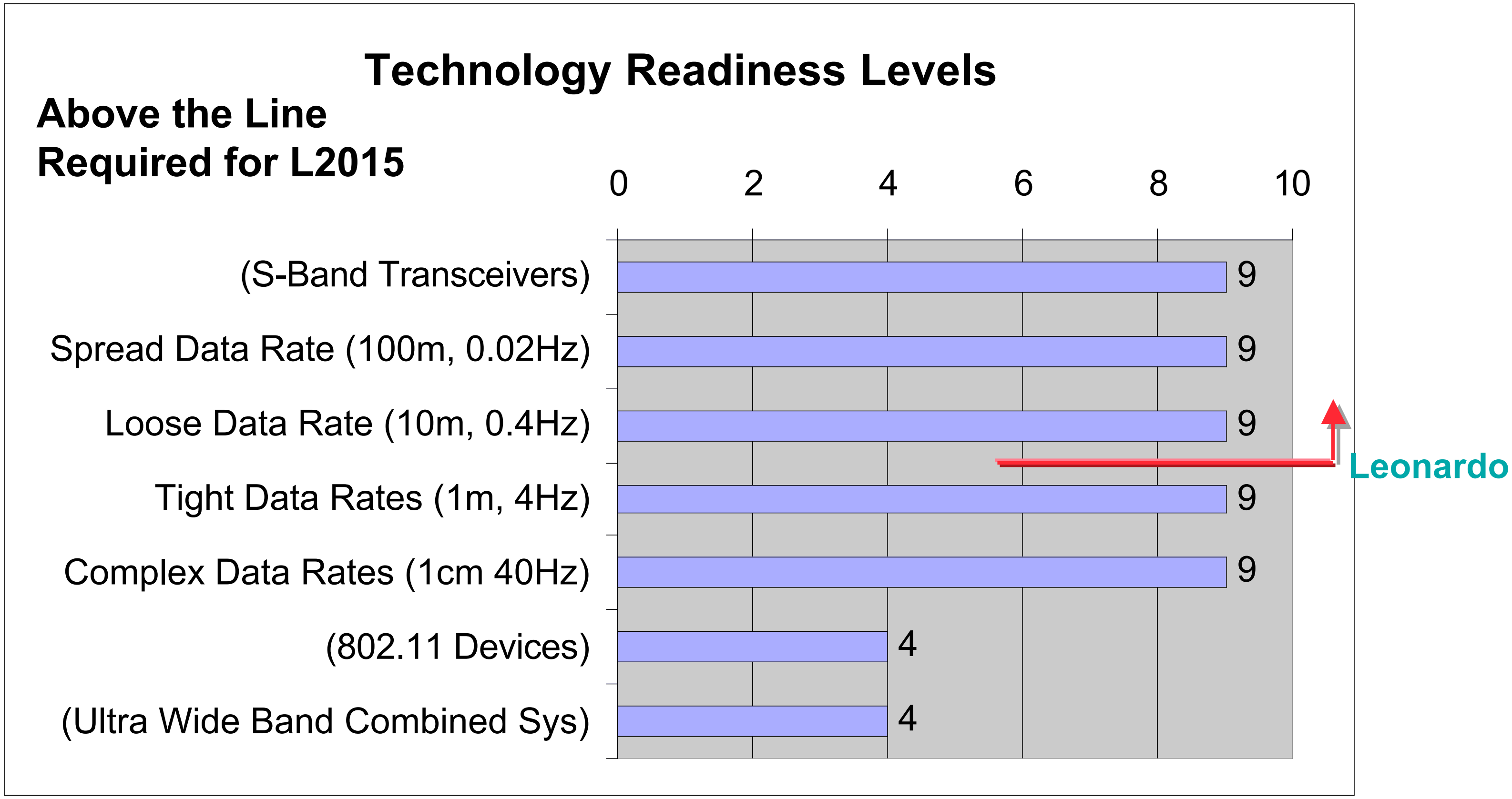
Formation Flying "Attributes"	Spread Formation		Loose Formation		Tight Formation		Complex Formation	
	Requirements	*ISL Data Rate Impact*	*Requirements*	*ISL Data Rate Impact*	*Requirements*	*ISL Data Rate Impact*	*Requirements*	*ISL Data Rate Impact*
Member S/C Attitude/ Position Knowledge	100m (>10m)		<10m		1m		10cm	
Member S/C Attitude/ Position Control	9.6 bits/sec per sat	f (n2 - n)		X 20		X 10		X 10
Member S/C Pointing Knowledge	1deg		5 min		30 sec		3 sec	
Member S/C Pointing Control	N/A							
Distributed GN&C (Formation)	28.8 bits/sec	f (n2 - n)		X 20		X 10		X 10
Autonomous/Distributed Formation Operations and Maintenance	0.02 Hz		0.4Hz		4 Hz		40 Hz	
Local Area Networking/ Distributed Formation Processing	63.587 kflops/sec	f (n2) + c		X 20		X 10		X 10
Timing/Synchronization	6 bits/min	f (n)		X 20		X 10		X 10
.....								
TCP/IP Overhead*	100%	X 2		X 2		X 2		X 2
For a 6 satellite formation:		**0.5 k bps**				**300 k bps**		**3 M bps**

Leonardo BRDF = 46 k bps total broadcast

(B.1.2) Comm-Based Relative Navigation Regimes



(B.1.3) Navigation Data Rates and Devices



Data Rates of 10kbps - 200kbps for Leonardo Not a Driver. Bigger Variable is Whether S/C is Separate From Payload and Whether the Router Can Direct the Data Appropriately.

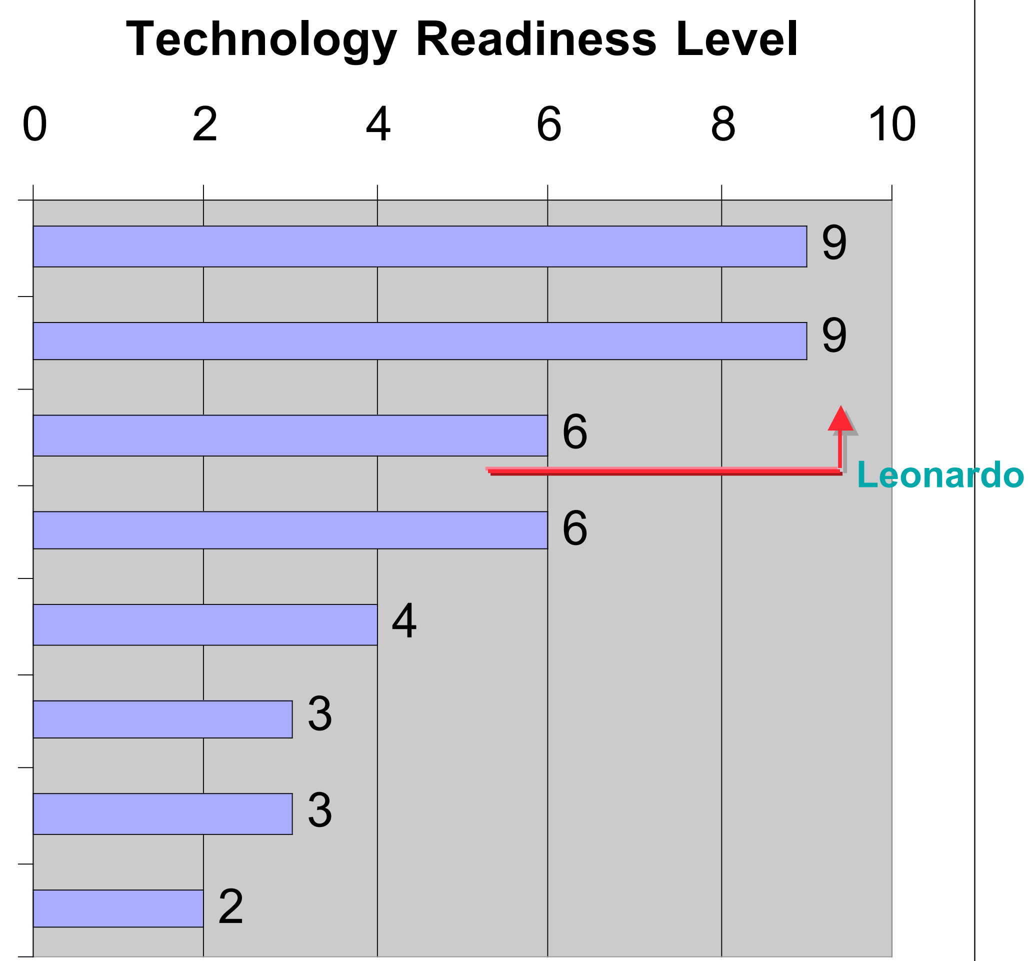
(B.2) Science Intra-Cluster Communications

Functions

- *High Data Rate Devices*
- *Routing*
- *Access Security*

(B.2) Science Intra-Cluster Communications

Above the Line
Required for L2015



Technology Area Presentation Roadmap (C)

Technology Area #A - Mission Operations

- (A.1) Guidance / Operations
- (A.2) Navigation (Orbital Control Systems)
- (A.3) Control (Attitude Control Systems)
- (A.4) Fault Detection Isolation and Recovery (FDIR)

Technology Area #B Intra-Cluster Communications

- (B.1) Navigation & Operations
- (B.2) Science

Technology Area #C - Spacecraft Infrastructure <<

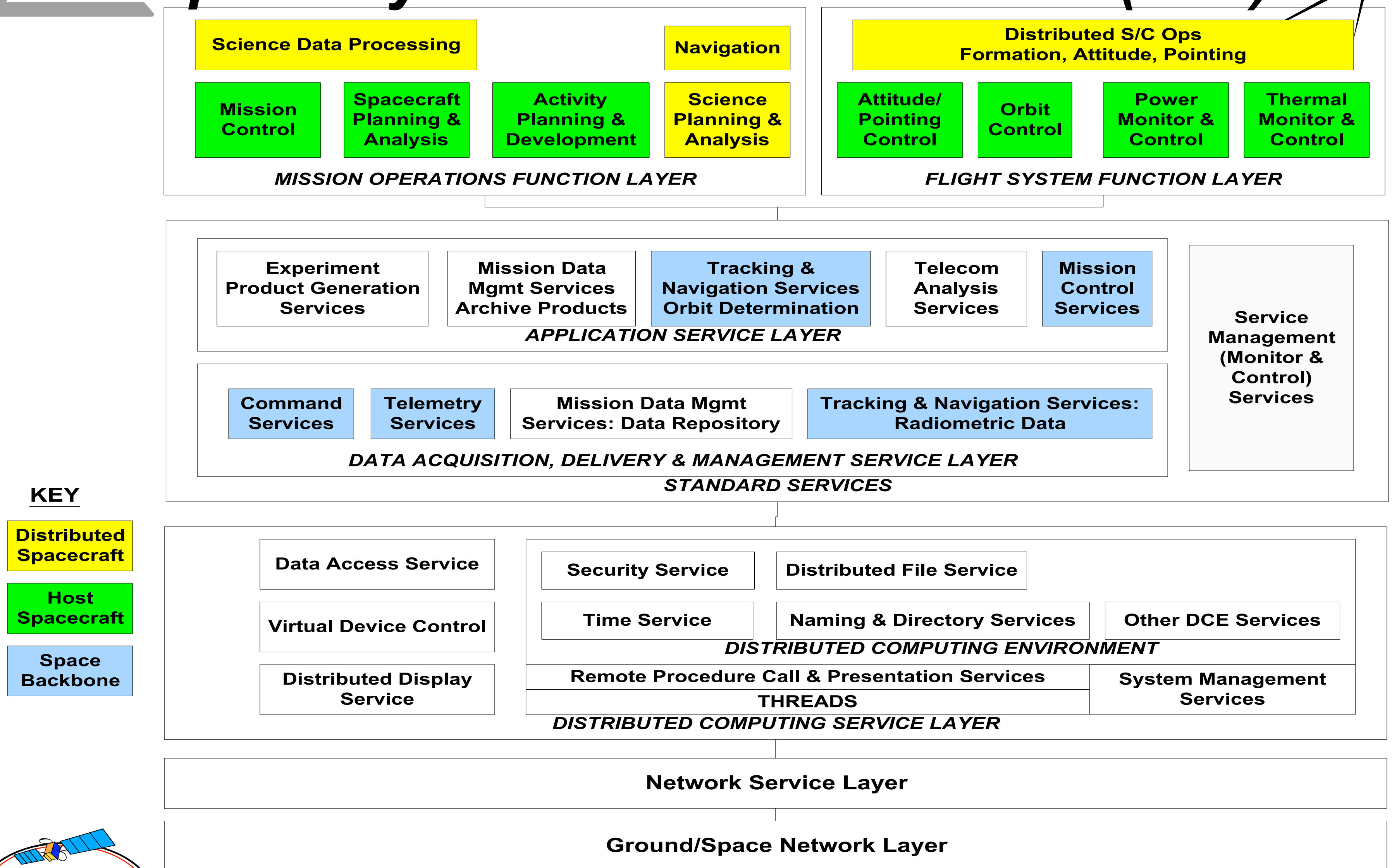
- (C.1) Data Bus (including Router)
- (C.2) Distributed Computing
- (C.3) Data Servers

(C.1) Data Bus

Functions

- Spacecraft Data Handling
- Separation of Payload and Bus
- Virtual Device Control
- Data Access Services
- Security Services

Space System Data Architecture (JPL)



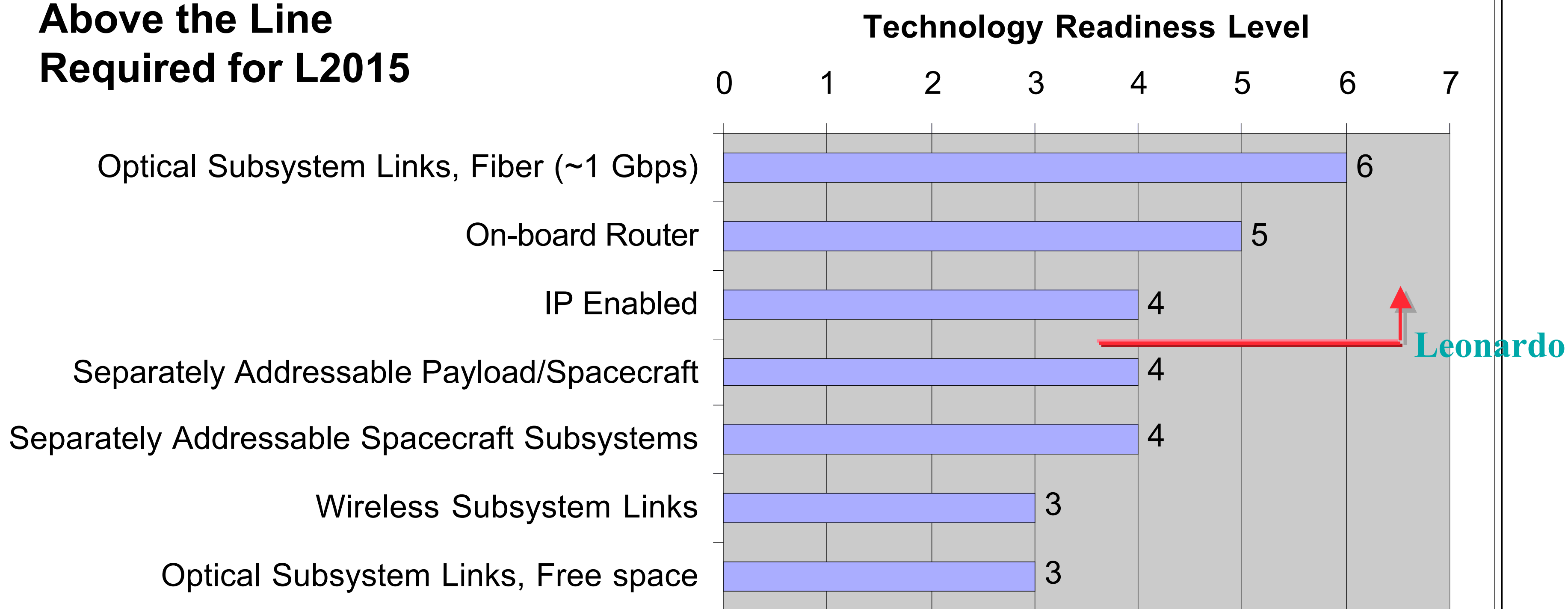
C&DH Component Technology Supporting Future Data Handling Systems

Dynamic Switch Matrix (AAE)

Optical Fiber Communications Interface (IMMS)

(C.1) Spacecraft Data Bus

Above the Line
Required for L2015

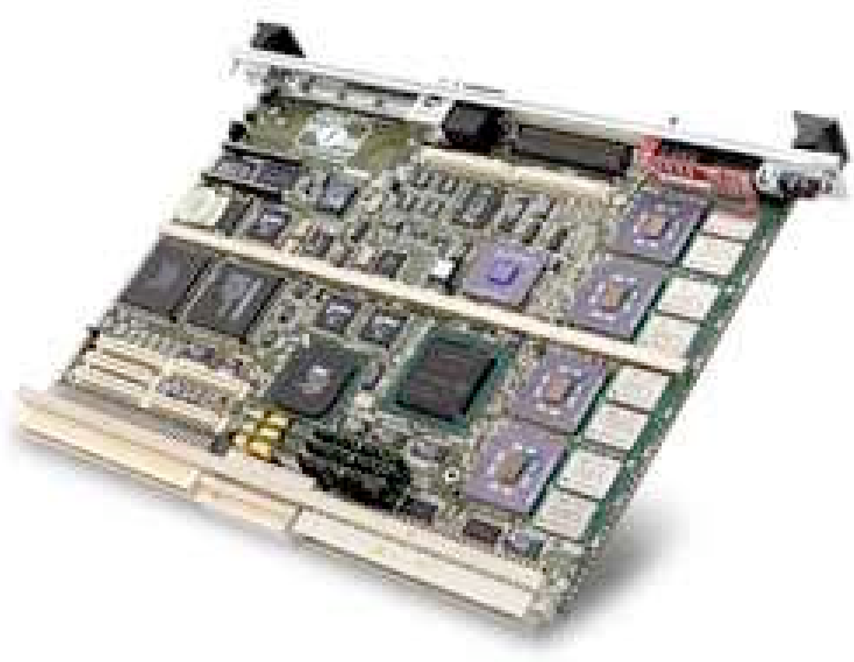


(C.2) Spacecraft Distributed Computing

Functions

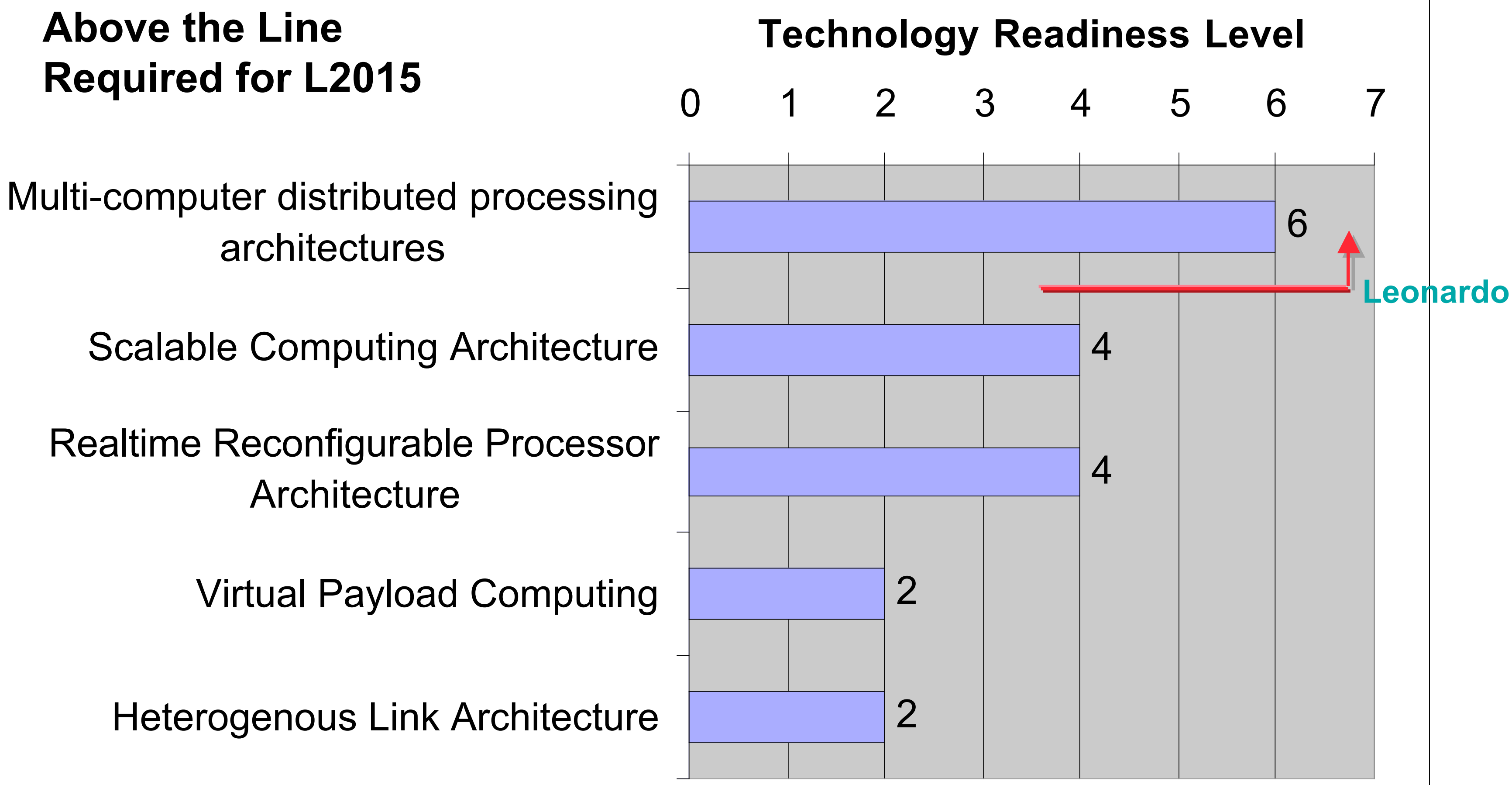
- Spacecraft Computing
  - Addressability
  - Scalability
  - Assignability
- Cluster Computing
  - Homogeneity
  - Assignability
  - Reconfigurability

Four-CPU (PPC-750) SBC Ground Version (Synergy)



(C.2) Spacecraft Distributed Computing

Above the Line
Required for L2015



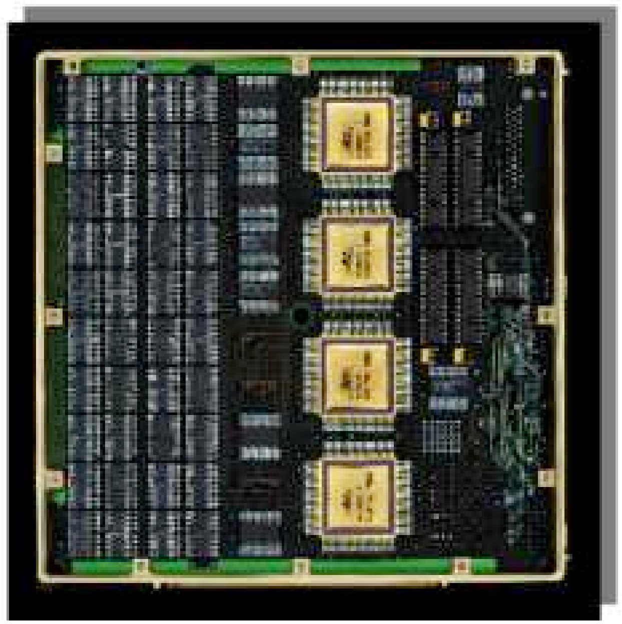
(C.3) Spacecraft Servers

Functions

- ***Data Servers***
- ***Application Servers***
- ***Communications Servers***

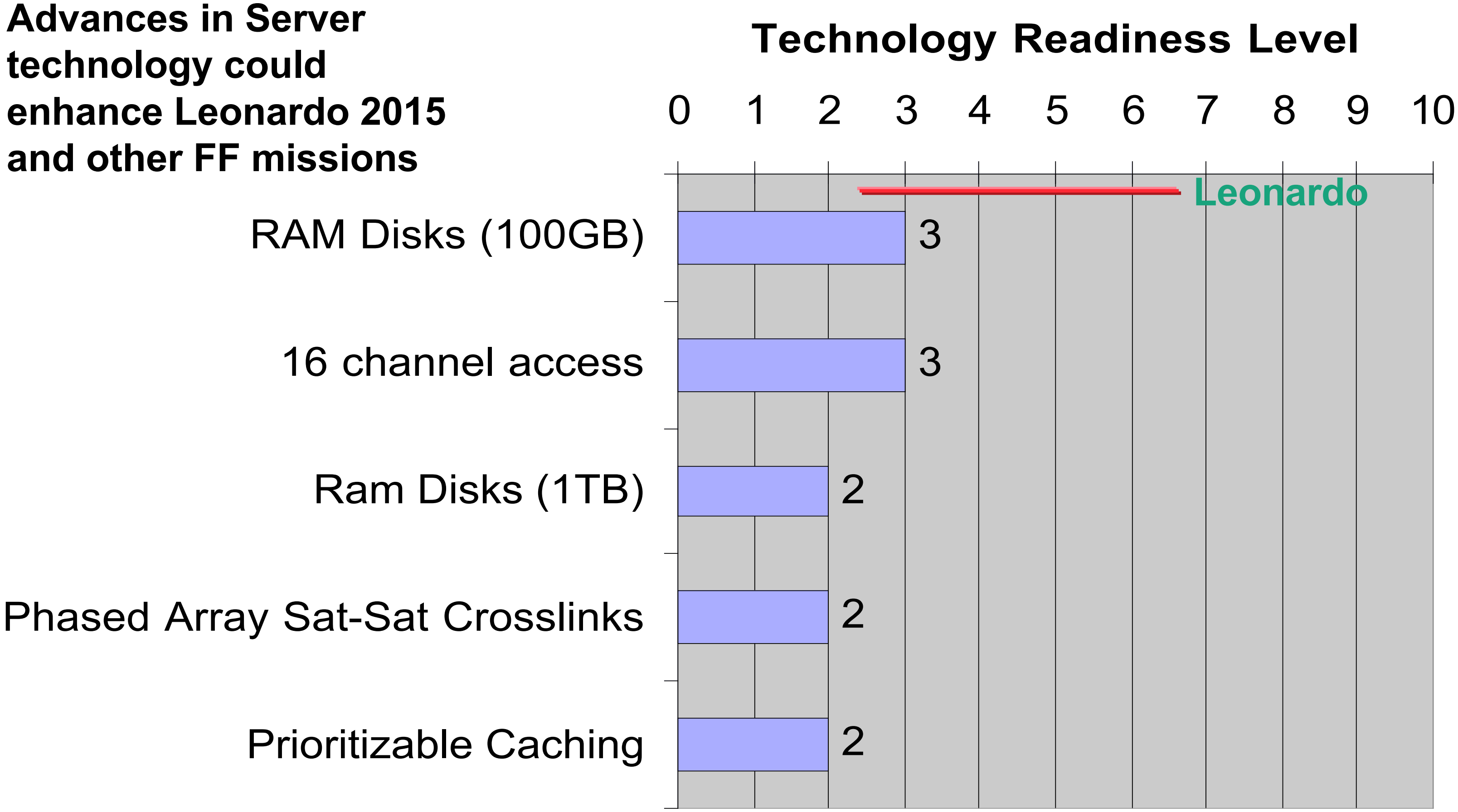
High Capacity Memory Module for Rosetta/Osiris

4 Gbits capacity (but up to 128 Gbits are currently available)



(C.3) Spacecraft Servers

Advances in Server technology could enhance Leonardo 2015 and other FF missions



Summary - FF Technology Assessment

Technology Areas			State of the Art			
			Available (7-9)	Qualifable (4-6)	Develop (1-3)	Comments
A	Mission Operations					
		Guidance/Operations			*	Coordinated & Autonomous Operations {science & payloads}
		Navigation	x	x		
		Control	x	x		
		FDIR	x		*	Autonomous Reconfiguration of Cluster
B	Intra-Cluster Communications					
		Navigation	x	x	*	Proximity Networks; Expandable Networks
		Science		x	*	Node Control and Configuration; Security
C	Spacecraft Infrastructure					
		DataBus			*	IP-enabled Spacecraft
		Distributed Computing		x	*	Hetergenous Links; Realtime Reconfigurable Architecture
		Servers			x	Not a near term requirement

Key:
x - Being Developed
X - Needs Acceleration

Development in These Key Technologies Supports FF in a SensorWeb Architecture

Key Formation Technologies

Leonardo 2015 Mission

Component Technologies Level

- Ultra Wide Band Combined Sys
- Node Control & Configuration
- IP Enabled
- Separately Addressable Payload/Spacecraft
- On-board Router
- Multi-computer distributed processing architectures

System or Functional Level Development

- Coordinated Attitude Control
- Coordinated Pointing Control
- Autonomous Formation Operations
- Autonomous Payload Operations for Cluster
- Coordinated Operations & Payload Data Collection
- Distributed Control Algorithms
- Multi-spacecraft Safing
- Autonomously Re-configurable Spacecraft
- Autonomously Re-configurable Cluster
- Coordinated Spacecraft Safing
- Closed Network Nav Data
- Expandable Network Nav Data
- Intra Cluster Routing
- Security - Multi-Ground Stations
- Security - Science Team
- Real-time Re-configurable Network Computing

Key Formation Technologies

FF Representative Missions

Component Technologies Level

- Collision Avoidance Sensor
- Proximity Beacon
- Ultra Wide Band Combined Sys
- 802.11 Devices
- Node Control & Configuration
- IP Enabled
- Separately Addressable Payload/Spacecraft
- On-board Router
- Multi-computer distributed processing architectures

System or Functional Level Development

- Coordinated Attitude Control
- Coordinated Pointing Control
- Autonomous Formation Operations
- Autonomous Payload Operations for Cluster
- Coordinated Operations & Payload Data Collection
- Distributed Control Algorithms
- Multi-spacecraft Safing
- Autonomously Re-configurable Spacecraft
- Autonomously Re-configurable Cluster
- Coordinated Spacecraft Safing
- Closed Network Nav Data
- Expandable Network Nav Data
- Intra Cluster Routing
- Security - Multi-Ground Stations
- Security - Science Team
- Scalable Computing Architecture
- Real-time Re-configurable Network Computing

Conclusion of FF Technology Evaluation

- SensorWeb could improve all proposed FF missions by providing a common infrastructure:
  - Real-time high bandwidth connectivity
  - Create virtual formations, increased ability to complete complex science / data collection missions
  - Standardized mission ops and interfaces lead to reduced system mission cost; re-partition spacecraft bus and payload
- Composite requirements of Leonardo plus all planned FF missions can lead to a SensorWeb imperative:
  - Additional technologies may apply as SensorWeb architecture evolves

Section 4: Communications Technology Assessment

George Silverman

Jeff Sroga

Presentation Outline

Leonardo "2015 and Beyond"

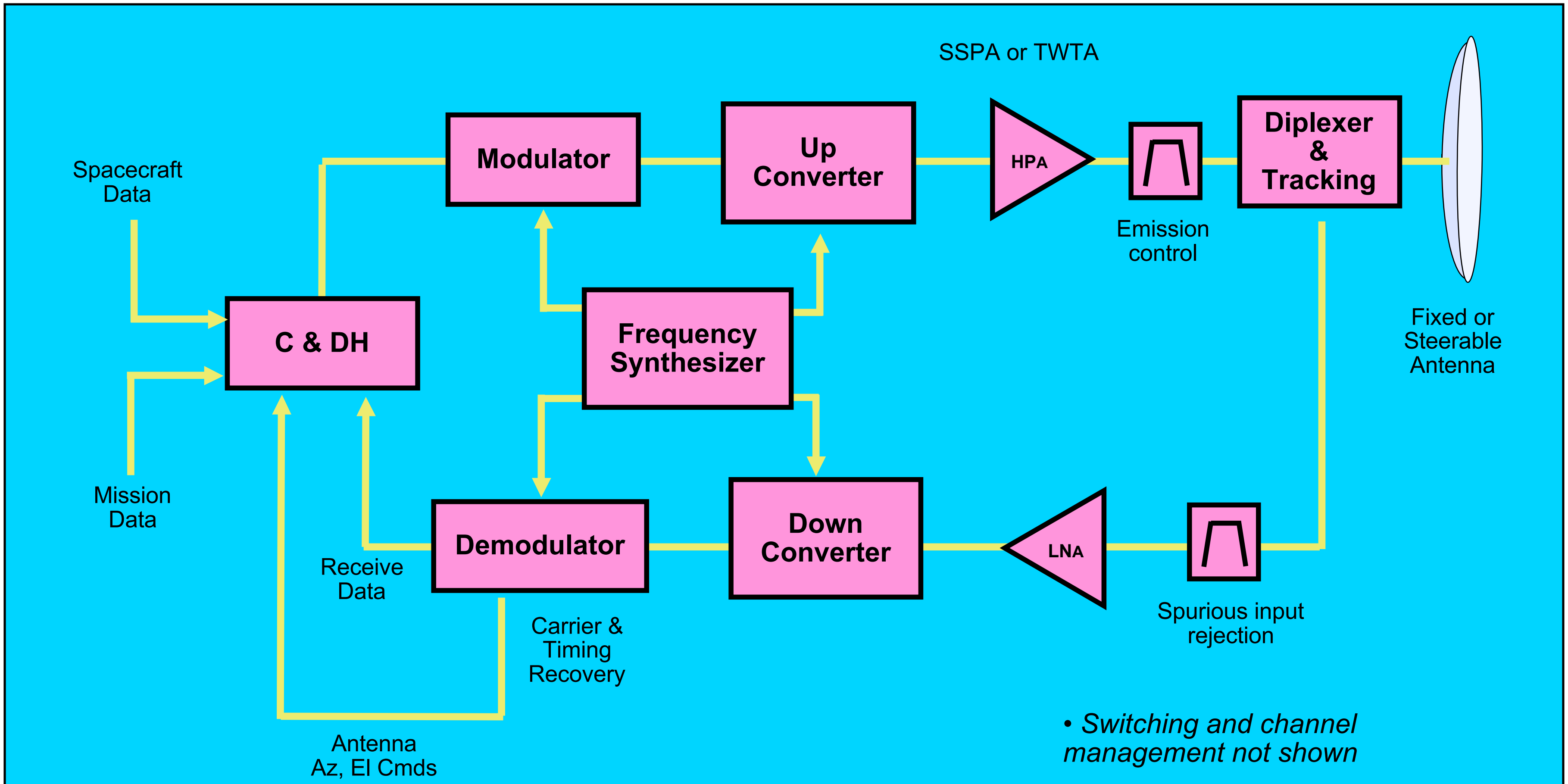
RF Communications Analysis Assessment

George Silverman
Space Systems Company
Lockheed Martin Corporation
January 28-30, 2002

Communications Technology Assessment

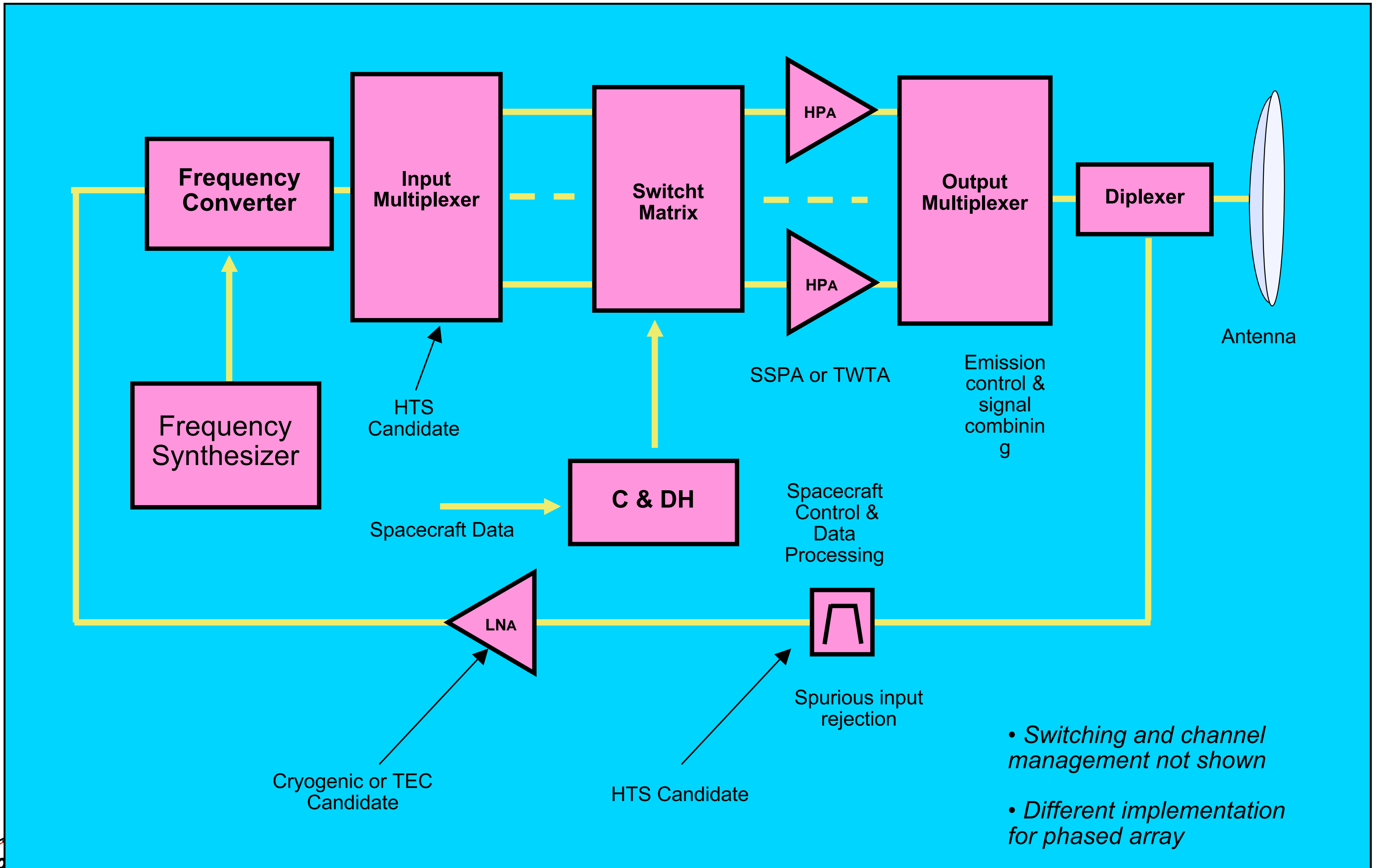
- RF Communication Architecture
- Phased Array
- Power Amplifiers
- High Sensitivity Receivers
- Modulators
- 60 GHz Crosslinks
- Photonic Applications
- Superconducting Microwave Components
- Mapping technology against the OSI model
- Technology Investments
- Phase III Program Recommendations

Spacecraft Data Communications Architecture - regenerative



- *Switching and channel management not shown*
- *Different implementation for phased array*

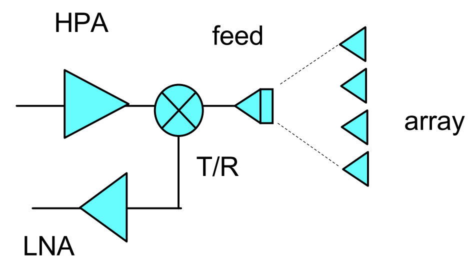
Spacecraft Data Communications Architecture - transponder



Phased Array Technology

Implementation

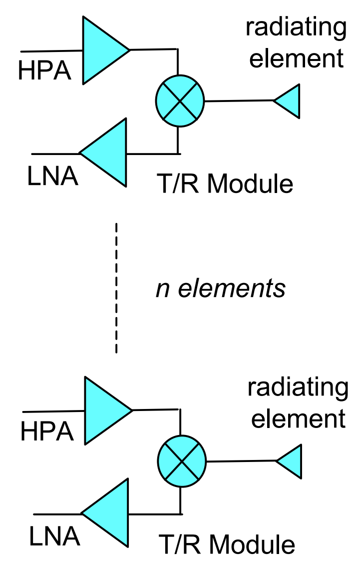
- Distributed or corporate fed
  Corporate fed typical of large ground-based radars
- Active - Transmit, receive, or full duplex



Corporate Fed Array

Why Phased Array ??

- Distributed amplifiers - Fault tolerant
- Vibration-free - no gimbal
  Ideal for instrumentation platforms
- Multi-beam, rapid scan
- Monopulse tracking
- Low power, high volume components



Active Phased Array

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Phased Array

Applications Summary

- Communications Relays *- GEO-Earth*
  - TDRSS-now, future TCP / IP nodes
  - Full-duplex - 30/20 GHz up- and downlinks
  - Frequency reuse - multiple access
  - 1 GHz available bandwidth - ITU limitation
- Communications Relays *- GEO-GEO, LEO-LEO*
  - TCP / IP nodes
  - Full-duplex - 60 GHz ISLs
  - Roughly 5 GHz available bandwidth
- Data Transmission - *LEO-GEO*
  - Tx only - 25 or 60 GHz, roughly
  - Vibration-free for critical optics
  - Multibeam, rapid scanning

Phased Arrays

How does performance compare to other designs ?

- **Dishes**
  - *Highest transmit gain*
  - *Highest receive G/T*
  - *Fixed antenna pattern*
  - *Mechanically steered*
  - *Can be mechanically defocused to alter beamwidth*
  - *Powered by high-efficiency TWTAs, SSPAs*
- **Shaped Reflectors**
  - *Midrange transmit gain*
  - *Midrange receive G/T*
  - *Tailored antenna pattern for specific ground coverage*
  - *Powered by high-efficiency TWTAs, SSPAs*
- **Phased Arrays**
  - *Lowest transmit gain*
  - *Lowest receive G/T*
  - *Multibeam capability, vibration-free scanning*
  - *Lowest power-added efficiency*

- **Typical Performance**

Antenna Type	Gain	EIRP
Parabolic dish	50-60 dB	90-110 dBm
Shaped reflector	40-45 dB	80-100 dBm
Phased array	40-45 dB	80-85 dBm

What's best ?? - Application-Specific

Dish	Highest EIRP
Shaped	Shaped power-on-ground distribution
Phased array	Angular & multi-beam agility

NASA Phased Array Activity

	HRUPAA Specification	GFSC Procuremnt Description	GFSC Microwave Systems Branch http://msb.gsfc.nasa.gov/technology/kaband.html	Paper Harris & AIL	GFSC Microwave Systems Branch http://jazzman.gsfc.gov/technology/kuband.html	EMS http://elmg.com/antenna_products/LEOarray.html	Instruments & Technology http://eol.gsfc.nasa.gov/technology/xpaa.html	NASA TDRSS H, I, J H Launched Summer 2000
Link	LEO-Earth LEO-TDRSS (H,I,J)	LEO-Earth LEO-TDRSS (H,I,J)	LEO-Earth LEO-TDRSS (H,I,J)	LEO-Earth LEO-TDRSS (H,I,J)	LEO-TDRSS (H,I,J)		LEO-Earth	TDRSS-Earth LEO-TDRSS
Frequency	25.25-27.50	25.25-27.50	25.25-27.50	25.25-27.50	Ku	Ku	X	S, Ku, Ka
Steering	+/- 60 degrees	+/- 60 degrees	+/- 60 degrees	+/- 60 degrees	+/- 45 degrees			
EIRP	33 dBW	34 dBW	33 dBW	33 dBW	5W into 23 dB gain 30 dBW		22 dBW	
Polarization	CP	LHCP	LHCP					
Sidelobes	-12 dB	-12 dB	-12 dB	-12 dB				
Data rate	350 Mbps OQPSK	4 Mbps QPSK	4 Mbps QPSK	100s Mbps to gnd 10s Mbps to TDRSS			105 Mbps	
Coding			Rate 0.5 FEC					
Input drive	0 dBm							
DC power			72 W	72 W				
Mass			5.2 kg	5.2 kg	4.5 kg		5.5 kg	
Comments		no moving parts		- Cites torque issue - Earth & TDRSS use same antenna - 240 antenna elements, 64 feeds - uses MEMS	torque & power issues	2-axis gimbal	- no moving parts - torque issue - 64 radiating elements	- Multibeam; to service several LEOs - Installed on TDRSS-H; failed to deploy - Dishes are identified, AJH thinks S-band phased array
Contractors		Harris, AIL		Harris, AIL		EMS	Boeing Phantom	Boeing
NASA partners		GSFC, Glenn						
Users		ATHP, EOS AM-2						
Funding source		SOMO						
Schedule		1999 protoqual		Demo Q2/02			Delivered 10/98	
Earth station		G/T: 23.4 dB/K 155 Mbps Rate 0.5 conv & RS 9.2 dB rain margin 1.9 dB link margin						

MILCOM 2001

Phased Array Papers

Who	Activity
Frankie Sutton et al Boeing Phantom Works	Planar Phased array SATCOM on-the-move - HMMWV 5 Mbps downlink, 256kbps uplink Ka band, 256 elements "Recent (prior to October 2001) demonstration"
William Jones Boeing	Similar subject as Sutton paper
Joseph Pelton George Washingto University & Arthur C. Clark Institute	Promotional paper and forcast Phased arrays on nanosats 100 spot beams on larger satellites Mobile tracking phased arrays on earth vehicles
E. Barry Felstead Communications Research Center, Ottawa, CA	Combining apertures on ships to reduce real estate Phased arrays application
Theodore Ioakimidis Mitre Corporation	Comercial Ka SATCOM on-th-move Hybrid technology - open-loop mechanical steering & phased array tracking by ground vehicle Mobile tracking phased arrays on earth vehicles - Army application

NASA Phased Array Papers

Emerging Communications Workshop (Aug 01)

Who	Activity
Jennifer Bernhard University of Illinois, Urbana	Multi-frequency, multibeam, multipolarization shared aperture Scan angles from broadside to endfire MEMS tuning TRL 3 to 4 transition end 2003
Richard Lee NASA Glenn Research Center	Multibeam Ka Distributed amplifiers, T/Rs Piezoelectric phase shifter, 5 degree phase resolution Activity funded at University of Colorado and Texas A & M TRL 3 to 4 transition by 2003
George Ponchak NASA Glenn Research Center	Integration effort for modules: T/R, MEMS, phase shifters Activity funded at University Arizona and Georgia Tech TRL 3 to 4 transition by 2002
Robert Romanofsky NASA Glenn Research Center	Ferroelectric reflector array Ka modules TRL 3 to 4 transition by 2003
Afroz Zaman NASA Glenn Research Center	MEMS components for phased arrays TRL 3 to 4 transition by 2002

University progress: 2 years per TRL
Some work is applicable to Leonardo 2015 + . . .

Power Amplifiers

TWTAs

Ka and below: 120 W, combinable to 240 W

60 GHz: 25 W Helix

50 W Cavity

Due to small dimensions @ 60 GHz, Helix tubes unreliable
25 W Coupled-cavity design & qualification required
50 W Coupled-cavity qualification required
Gain flatness an issue - linearization required

SSPAs

Ka and below: PAE: 25 to 30 %

60 GHz: PAE: ≤ 15%

Output stage PAE > 60% with overall amplifier PAE ≥ 50% desired
Need to reduce prime power demand and heating; goal is to reduce thermal dissipation and power required for phased array transmitters
Data includes power conversion efficiency
Gain flatness an issue - linearization required

High Sensitivity Receivers
LNAs

LNA Noise Figure - today

C and below:	NF < 1 dB
Ku-band :	NF < 2 dB
Ka-band:	NF 3 dB
V-band:	NF 4 dB

NF of roughly 1 dB is desired for all bands; data rate varies directly with NF

Amplifiers may require cooling

TEC for phased array applications

Cryogenic for single-amplifiers relays

LNA Bias Power

15 mW per 10 dB gain stage typical today

5 mW per 10 dB gain stage achievable with InP

Development is required; goal is to reduce thermal dissipation and power required for phased array receivers

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LMCSS

High Sensitivity Receivers

Modulators

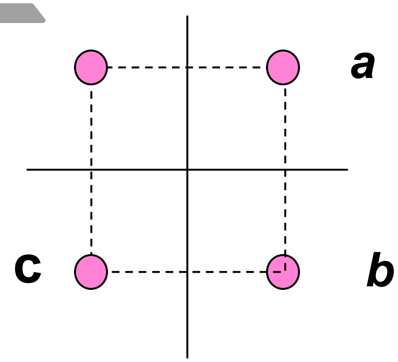
- **BEMs of 16, 32 QAM are easy to conceive & design**
  - *Digital synthesis (software radio)*
  - *Analog components*

- **Issues**
  - *HPA & LNA gain flatness over frequency band*
  - *Required Eb/No increases with increase in bits/symbol*
  - *Estimates of Eb/No depend on system linearity*

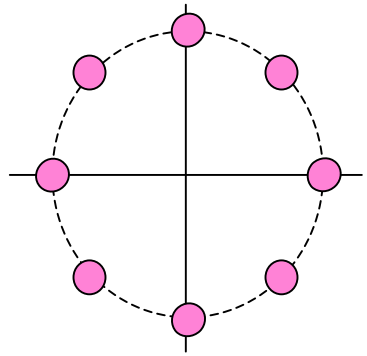
- **MSK & FPSK is viable option to QPSK for 2 bits/symbol**
  - *QPSK varies 3-dB between points of constellation*
  - *MSK & FPSK Signals are constant envelope*
    - *3 Gbps has been demonstrated*
  - *Bandwidth is increased 1.5 factor*

- **What do we need ?**
  - *A high order constant envelope modulation (3 or more bits/symbol)*

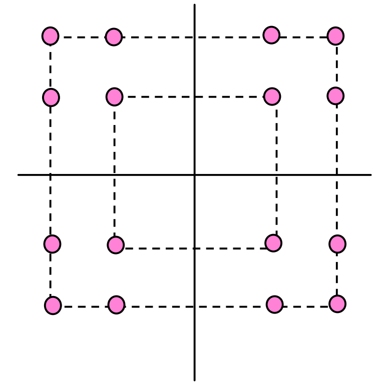
Bandwidth Efficient Modulation



QPSK
2 bits/symbol
2^2 = 4 states



8-PSK
3 bits/symbol
2^3 = 8 states



16-QAM
4 bits/symbol
2^4 = 16 states

- *Distance between states decreases as number of states increase*
- *Error probability increases*
  - *A trade between bandwidth efficiency and Eb/No - EIRP or receiver sensitivity*
- *AM-PM conversion - creates ISI*
  - *eg., transition from **a** to **b** is 3 dB AM and **a** to **c** includes a zero crossing!*
  - *Drives HPA back-off, gain flatness over frequency, & linearization*
- *QPSK 2 bits/symbol alternatives*
  - *MSK, CVSD, . . .*
- *Higher Order - No reports*

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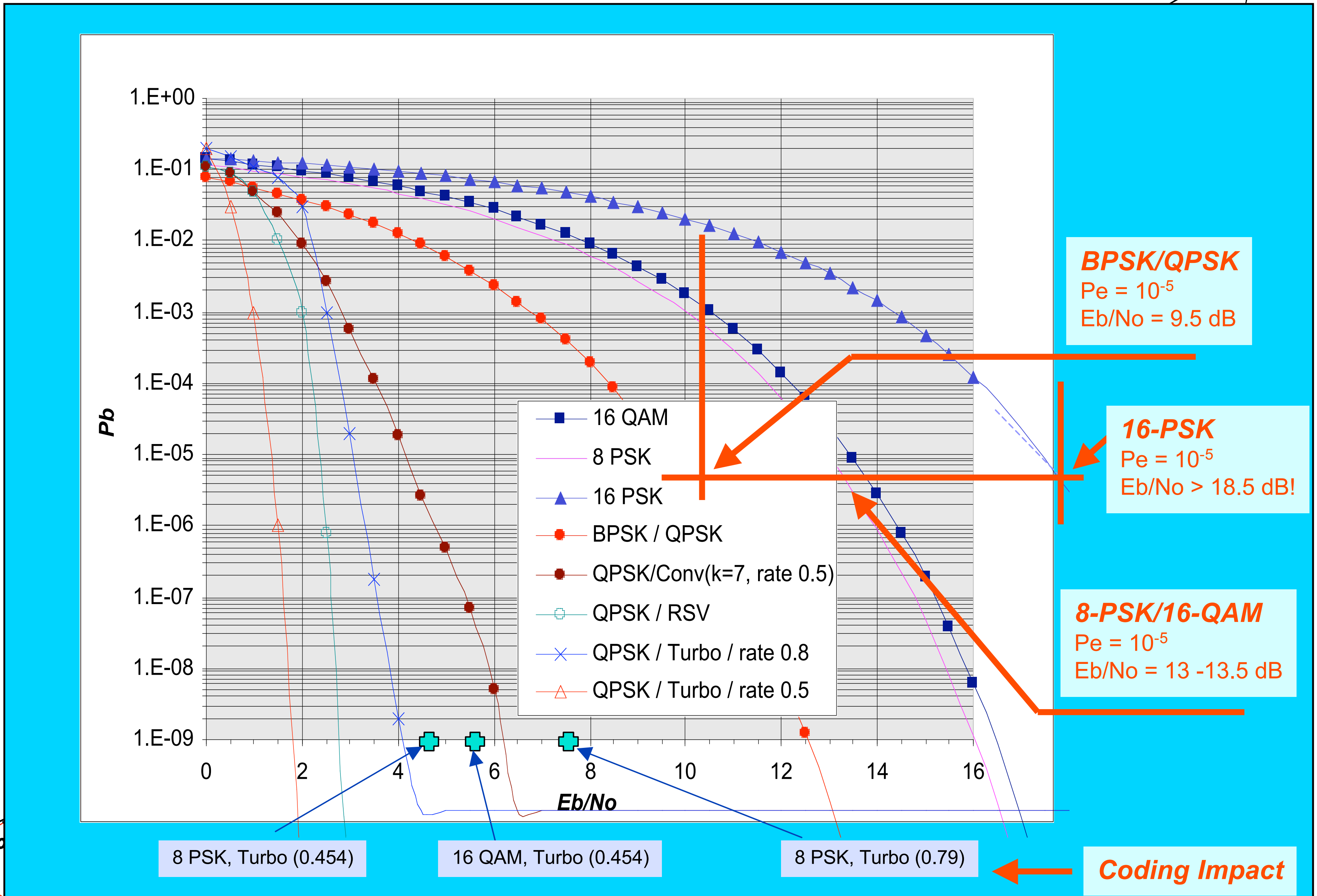
Eb/No & Error Rates

for various modulation schemes



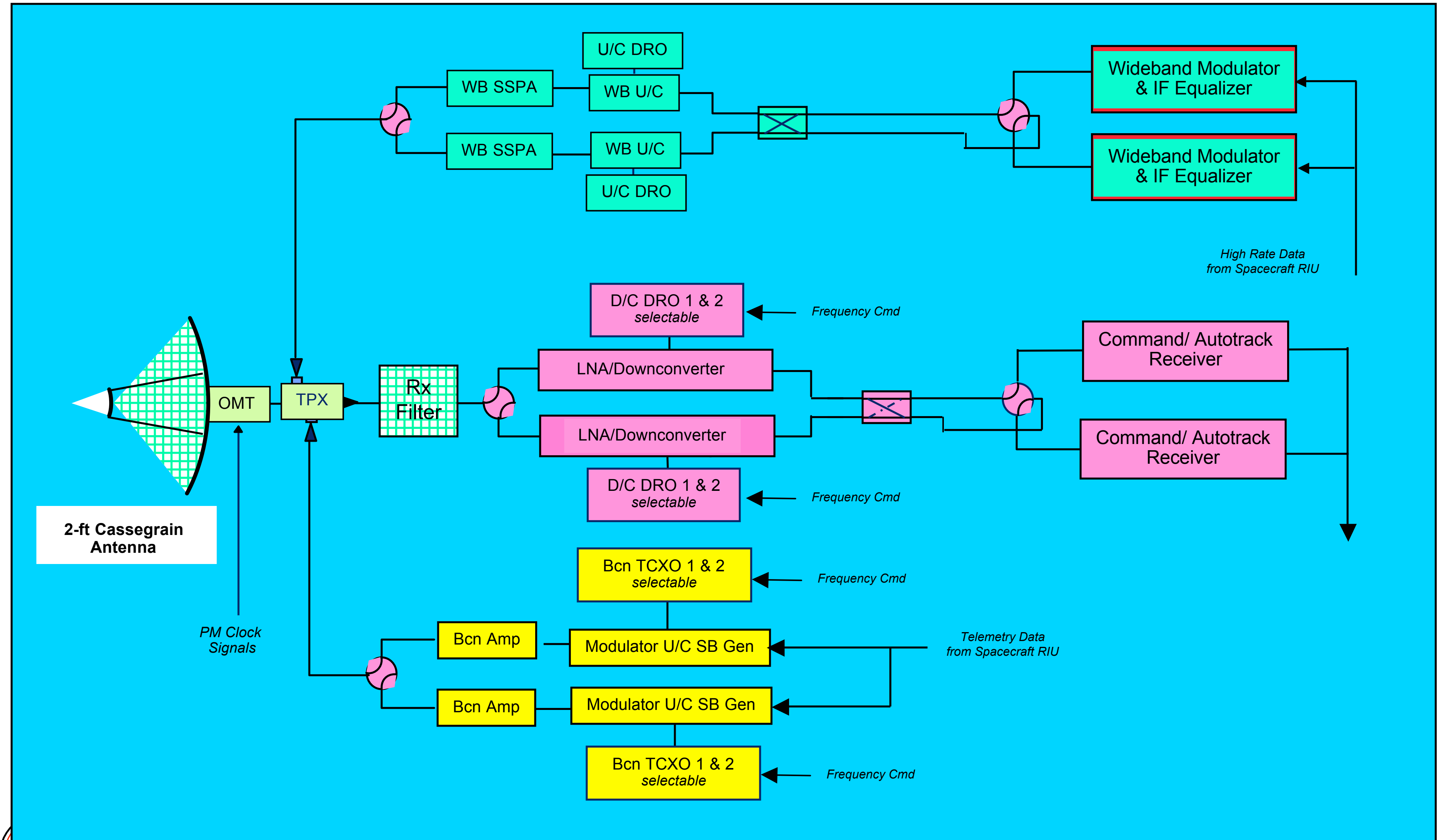
RF ISLs - Intracluster - V-Band

Leonardo 2015 + ...

- Typical design & topology
- Frequency considerations
- EIRP requirements
- Component development required & roadmap

60 GHz Crosslink

LM Product



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LMCSS

Leonardo Communication Link Methodology

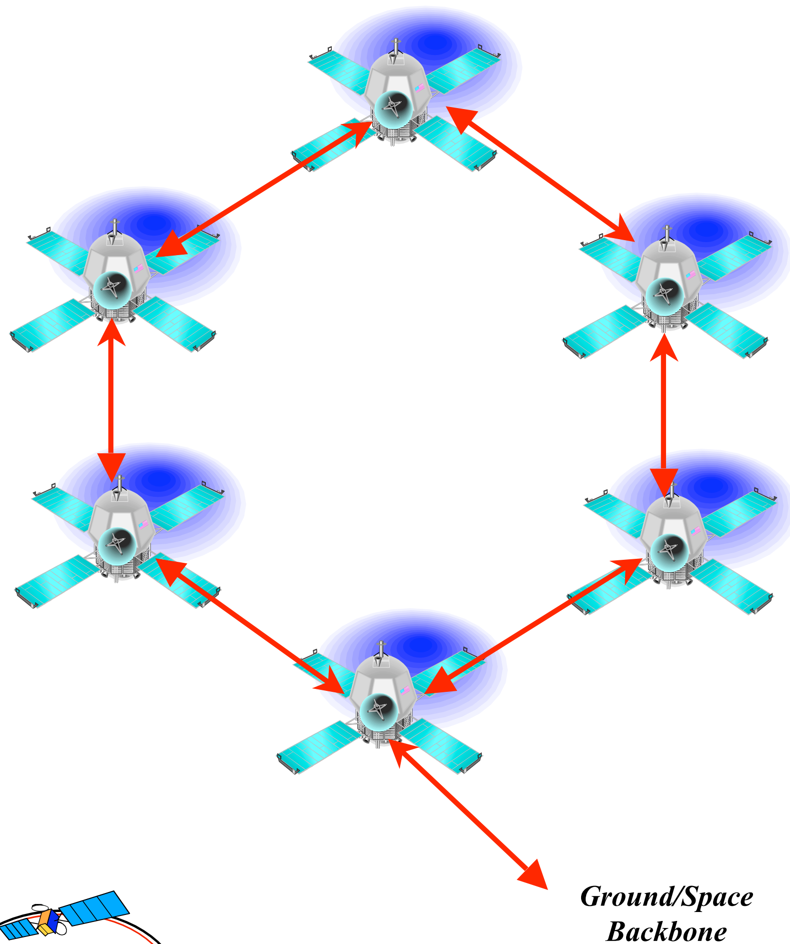
- **Methodology**

  Analyze Intracluster link performance
  Determine EIRP to support various communications data rates
  Examine impact of antenna gain on RF power requirements
  - gimbaled reflector & phased array
  Compare RF power needs to State-of-the-Art
  - solid-state & electron tube
  Coding impact on BER - BER = 1×10^{-9} (min for IP traffic)
  Bandwidth constrained to 4 GHz at 60 GHz carrier
  Redundancy not addressed here

- **Data Rate Requirement**

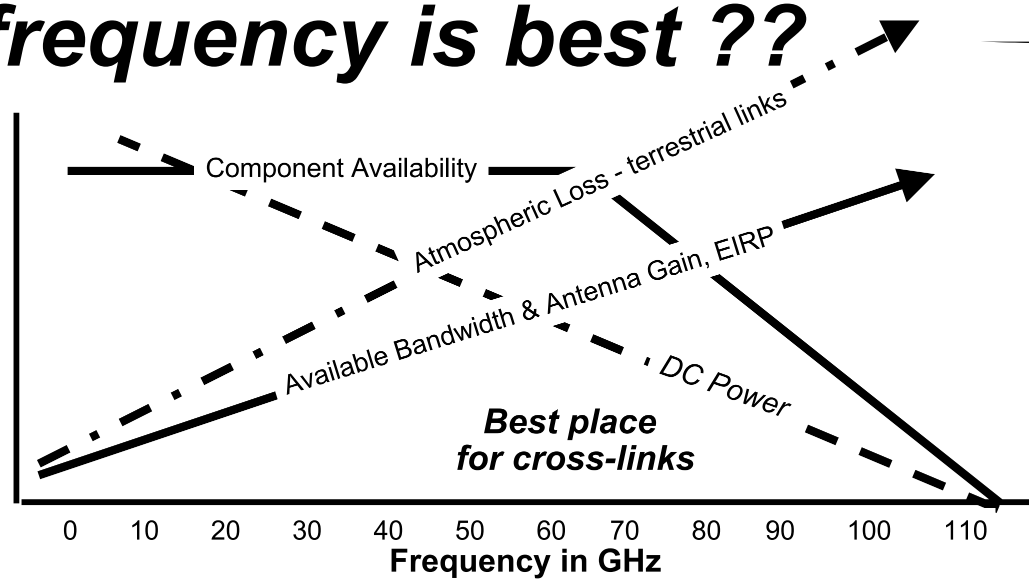
  Instrument requirements Identified next page
  Trade limits: OC-1 to OC- 192

Intracluster Ring Topology



- Ring Topology for Leonardo “2015” (6 S/C)
- Symmetric, bi-directional intracluster links
  - Two links per spacecraft
- Data transmitted (pipelined) through member S/C to “central” S/C for data distribution to ground user
- “Baseline” example for ISL raw data transfer requirements (271Mbps/instrument, 50% duty cycle)
  - real time: 3X raw data rate (813Mbps)
  - orbit average: 1.5X raw data rate (407Mbps)
- On Board Processed data rate- dependent on distributed processing connection bandwidth requirements
- Alternative is Star Topology
  - One link per spacecraft
  - High data rate for nucleus member only
  - Topology drives redundancy design

What frequency is best ??



- **Lower Frequencies**

  RF power easier to generate
  Less "legal" bandwidth available
  Better for up & down links - atmospheric & weather issues

- **Higher Frequencies**

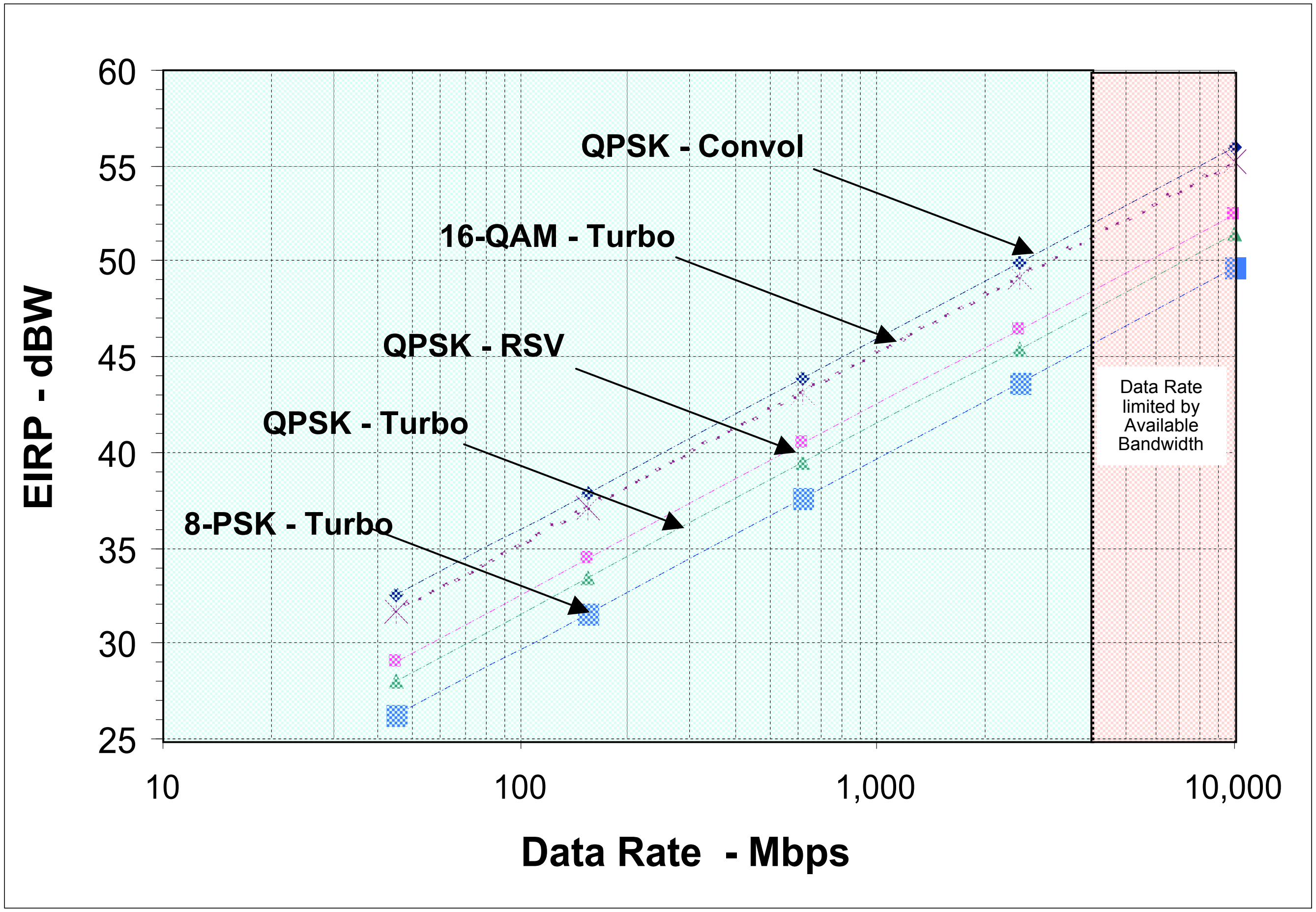
  Physically small components
  - antennas, waveguide, couplers
  Antenna gain easier to obtain
  Better for crosslinks - no atmospheric & weather issues

- **System Considerations**

  For same size antenna, gain increases with frequency
  Hence EIRP increases with frequency for same RF power
  Hence less prime DC power required
  But loss increases with frequency

Transmitter EIRP - Leonardo 2015 . . .

for several modulation & coding schemes



EIRP Required for 2,000 km intracluster data link

Frequency: 60 GHz Bandwidth: 4 GHz

Data at OC-1, -3, -12, -48, & -192

RF Power - *how much is needed ?*

RF Power = EIRP - Antenna Gain

- **How much EIRP ?**

  previous chart

  52 dBW (max)

- **RF power**

  52 dBW - 46 dB = 8 dBW

  □ 6.5 W

- **What kind of Amplifier ?**

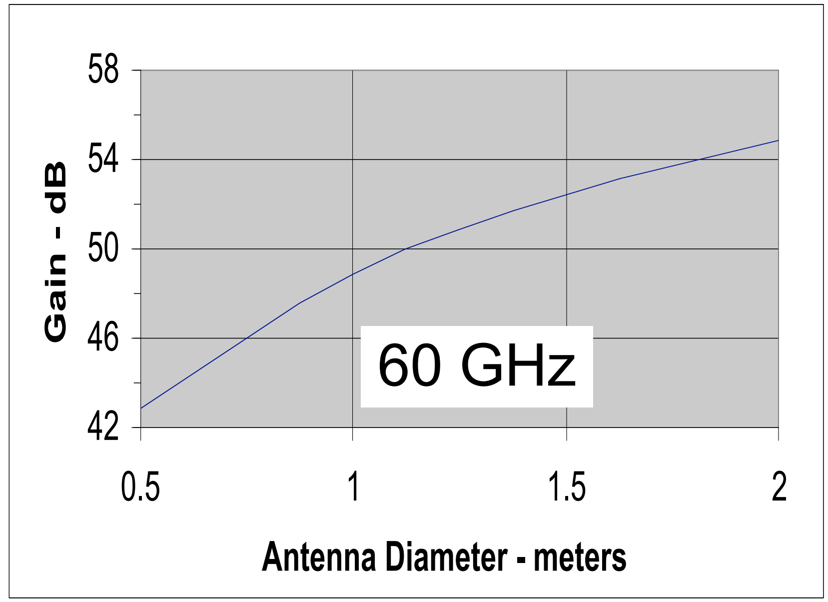
  6.5 W SSPA

  Development required

  Off-the-shelf SSPA - nominal 2-W

  Target nominal 10-W

  Technology: 0.1 □ PHEMT on GaAs



Antenna gain v diameter

use 46 dB □ 3/4 m

- **RF losses**

  All data includes feed loss associated with generating autotrack signal

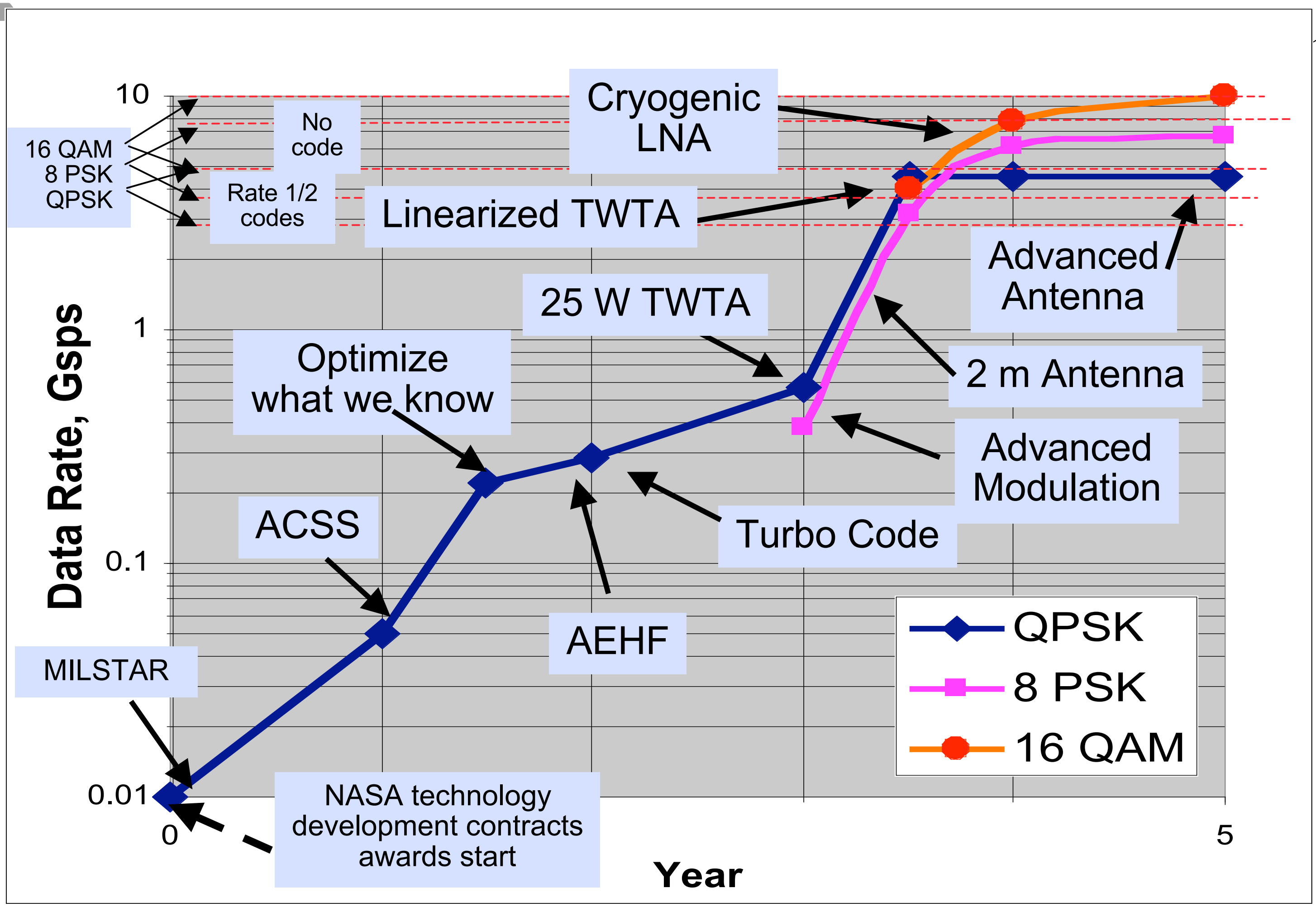
60 GHz Crosslink

Development required for certain critical components

some RF components exist at TRL 9
others are at performance levels below that required for advanced NASA missions
Development effort required to raise TRLs to flight qualified

	Present	Required
RF power	1-2 W	10 W *Present: Lab demo at TRL 3*
Modulator & Demodulator	QPSK @ 100's Mbps	8-PSK & 16-QAM @ Gbps *Present: Lab demo @ TRL 3*
Digital processor Coding & decoding Bus data processing Data routing	35 MIPS *Rad 6000*	several hundred MIPS *Rad 750 @ TRL 6*
Software/Firmware Coding & Decoding		Upgrades required

Fast Track 60 GHz ISL Roadmap



Path to 10 Gbps without development cost constraints and optimized schedules

Fully integrated program - driven by National Imperative

A QRC program

Photonic Developments

Government Sponsored Programs

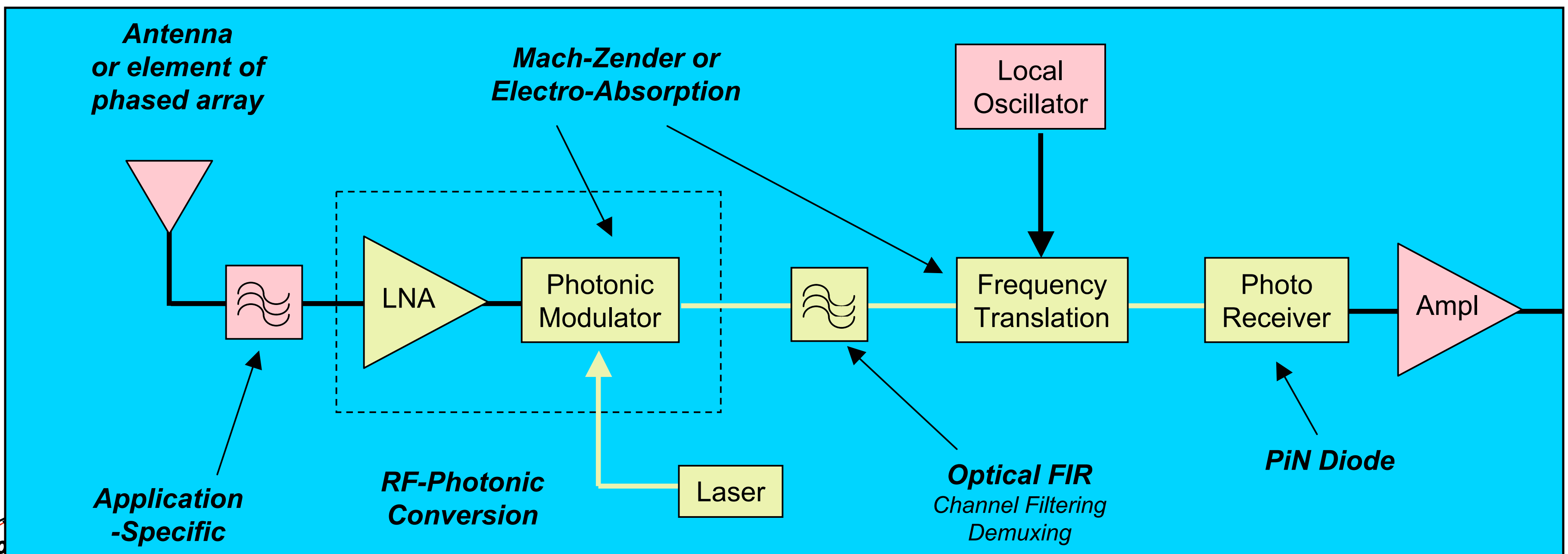
NASA

OEIC Cross Enterprise Technology Development Program
Phased array interface applications

Air Force

Wideband Agile Receiver
ELINT, SIGINT, COMINT applications

Objective *- develop monolithic photonic components*
- low weight, low power, high reliability



Photonic Applications

Commercial & Defense COMSAT

- Mass & component cost reduction
  - *120 kg out of 800 kg & $3M cost reduction*
  - *See example - follows*
- Phase stable signal and control transmission
  - *Wideband, flat group delay*
- Frequency-independent beam forming
  - True time delay
- Component development
  - *Leverage off commercial telecom*
  - *Some components virtually off-the-shelf*
  - *Some require "6.2" effort*
  - *All require space qualification*

Photonic and RF Transponders

Mass & Cost Comparison

Commercial COMSAT Characteristics

Ku-Band: 48 Inputs, 32 TWTAs Ka-Band: 8 Inputs, 10 TWTAs

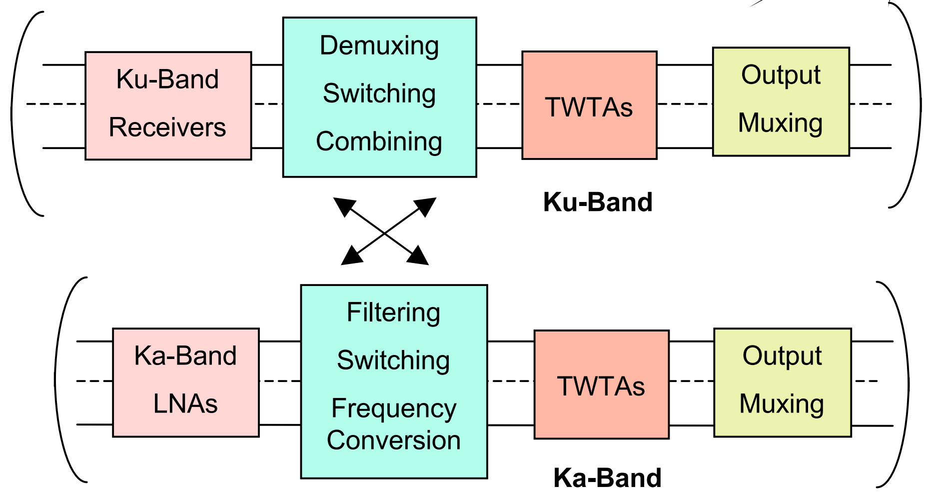
H & V Polarization

Cross strapping: Ku - Ka

Photonic Transponders

Same capability

Comparison includes TT&C, antennas, etc



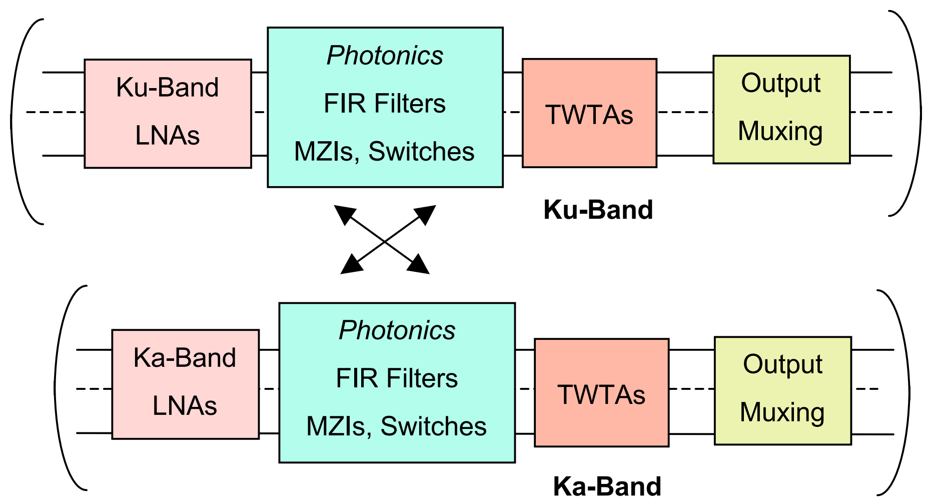
Conventional RF Design

Photonic Benefits to Spacecraft

Reuse of common components
Sharing of optical modulation/detection
Reduced mass due to use of glass
Reduced mass due to high density packaging

Impact to Spacecraft

Mass reduced ~ 120 kg
Cost reduced ~ 5% to 10%



Photonic Design

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Superconducting Microwave Components

- **Microwave applications**

  Filters, multiplexers, couplers, . . .
  Wherever stripline technology applies

- **Recent NASA-Sponsored Effort**

  Technology Reinvestment Program with Lockheed Martin et al

- **Program Status**

  Engr Model 60-channel multiplexer completed functional test
  Qual Model 60-channel multiplexer entering test program
  Qual Model Cryo LNA and input filter entering test program

- **Features of Superconducting Microwave Components**

  Low Mass - high k substrates make very small components
  Low Noise - cryogenic temperatures yield very low Johnson noise

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Technology Investments
System Issues

Antennas & Phased Arrays

Development Area	Application
Phase shifters	High resolution imaging
T/R modules	Data transmission, reception
Photonic integration	Aperture sharing
MEMS	
Unfurlable reflectors	

Software

Coding algorithms - improve effective Eb/No
Network operation, shared processing
Autonomous operation
Navigation & tracking

Technology Investments
Components

Power Amplifiers

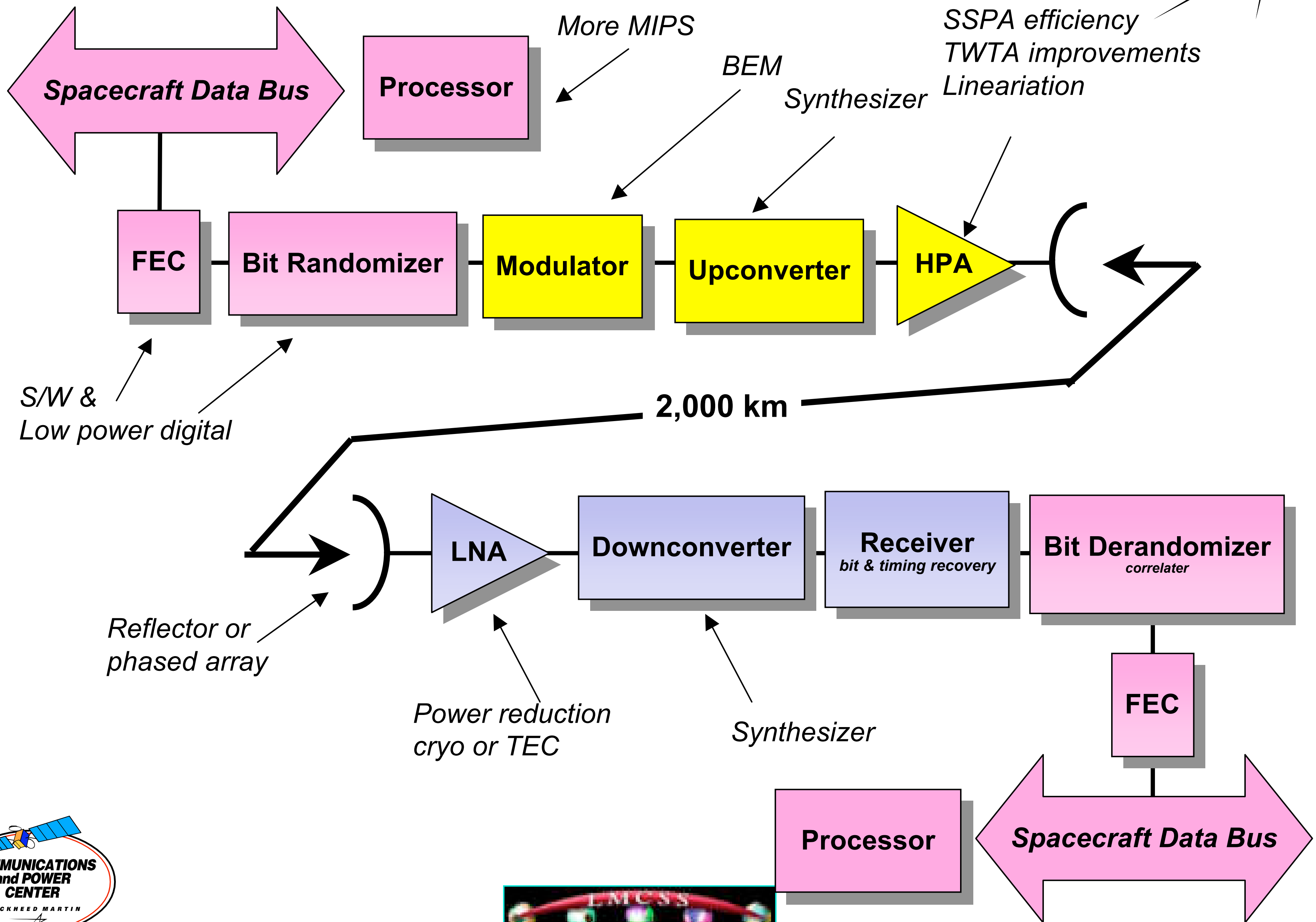
Item	*Engineering Effort Required*
25W TWTA	Cavity- coupling & linearizer development
50W TWTA	Space qualification
SSPA	High efficiency developments output PAE > 60%, amplifier PAE > 50%

High Performance Receivers & Modulators

Item	*Engineering Effort Required*
Frequency Synthesizers	Power reduction Channel management - fine & gross tuning
LNAs	Noise figure 1 dB at Ka & V-band Cryo & TEC cooling Low bias power - InP - reduce array heating
Modulators	Minimize AM-PM 3 to 5 bits/symbol
Photonics	Light weight switching & interconnect Phase-stable signal transmission Filtering & demuxing Frequency-independent beamforming
Low power digital circuits	Data coding & formatting

Technology Investment

Where in the system ?



Mapping Technology to OSI Model

Key Technologies

OSI layer	Key Technologies
Application Software OSI Levels 5-7	Data Processing Autonomous operation Auto-scheduling, Shared computing Navigation & tracking ***Software Creation***
Transport OSI Level 4	TCP Management Software File transport, error correction Interface software ***Algorithm Upgrades***
Internetwork OSI Level 3	Packet Management IP, UDP, etc transport Error correction Interface software ***Algorithm Upgrades***
Datalink OSI Level 2	Media Access Data transport, parity, checksum Interface software ***Low power digital development***
MODEM Physical Layer Transceiver OSI Level 1	Media ***Power amplifiers, LNAs*** ***Modulators*** ***Low power digital & Photonics*** ***Antennas***

Common Processor
Levels 3-7
Low power & mass
Processors, FPGAs, Memory

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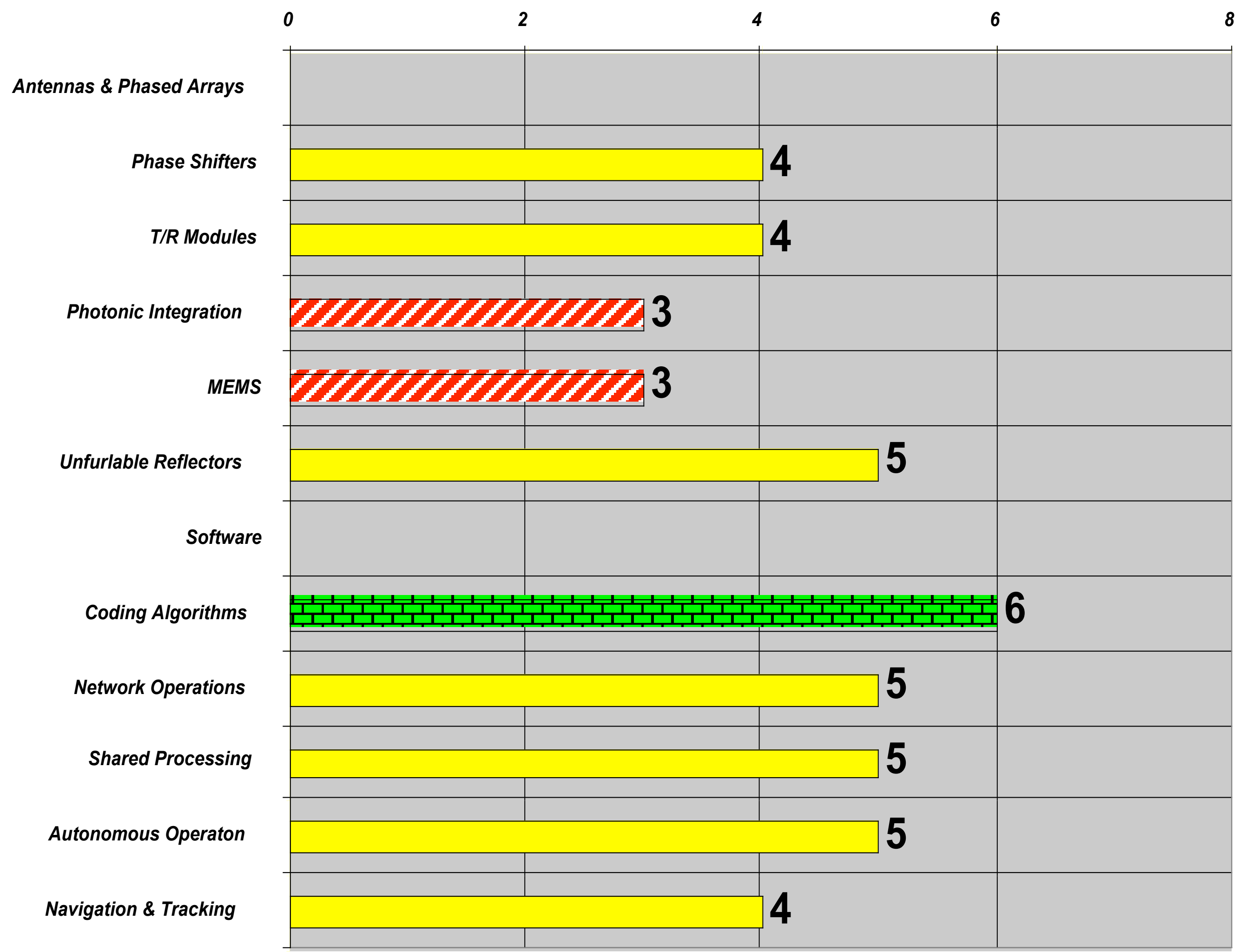
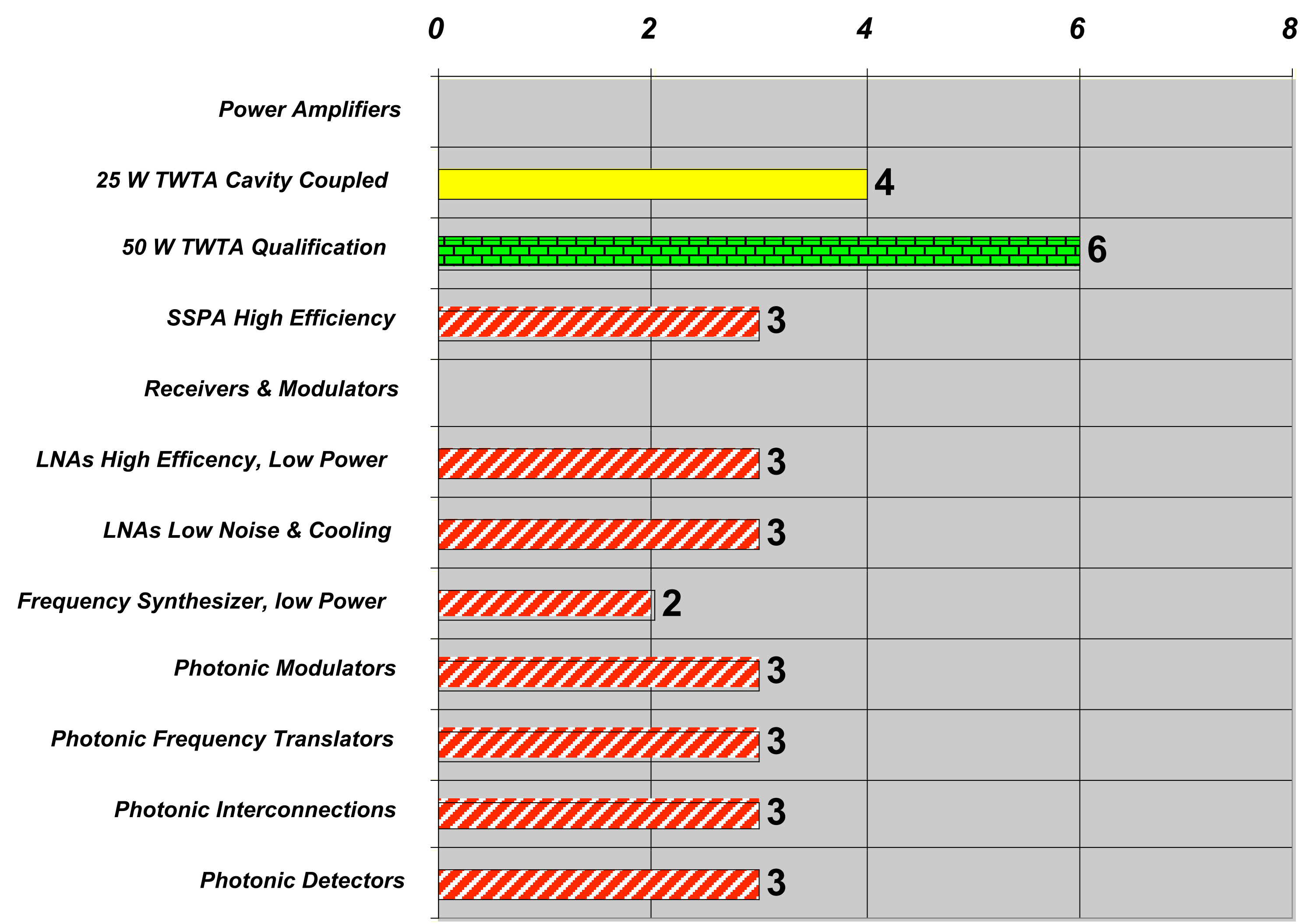
TRL Assessment
System Components



TRL Assessment
Electronic Components



Top Five RF Communications Developments Needed

- **Constant envelope bandwidth efficient modulator**
- **LNAs - Low noise, low bias power at Ka and V-band**
  Technology today: 0.1 □ InP, single heterojunction, < 1V
- **SSPA power-added efficiency improvements**
  Technology today: 0.1 □ GaAs, PHEMT single heterojunction, □ 3-4 V
- **Photonic component maturation**
- **Network Software**

Phase III Follow-on Recommendations

- **Constant envelope bandwidth efficient modulator**

  WHY: *Reduce linearity problems in RF power generation*

  HOW: *Optimize state transitions*

- **Transistor morphology investigation**

  WHY: *System performance improvement driver at Ka- and V-bands*

  HOW: *Optimize material for low noise and low bias power LNAs*

  Improve Linearity - - see example next page - -

  Improve temperature stability

  Technology Survey

  - MHEMT InP on GaAs

  - GaN high voltage devices

  - SiC high temperature, high power

  - Amplifier architecture- adaptive control

  - Power conversion efficiency architecture

- **Program Plan (for both)**

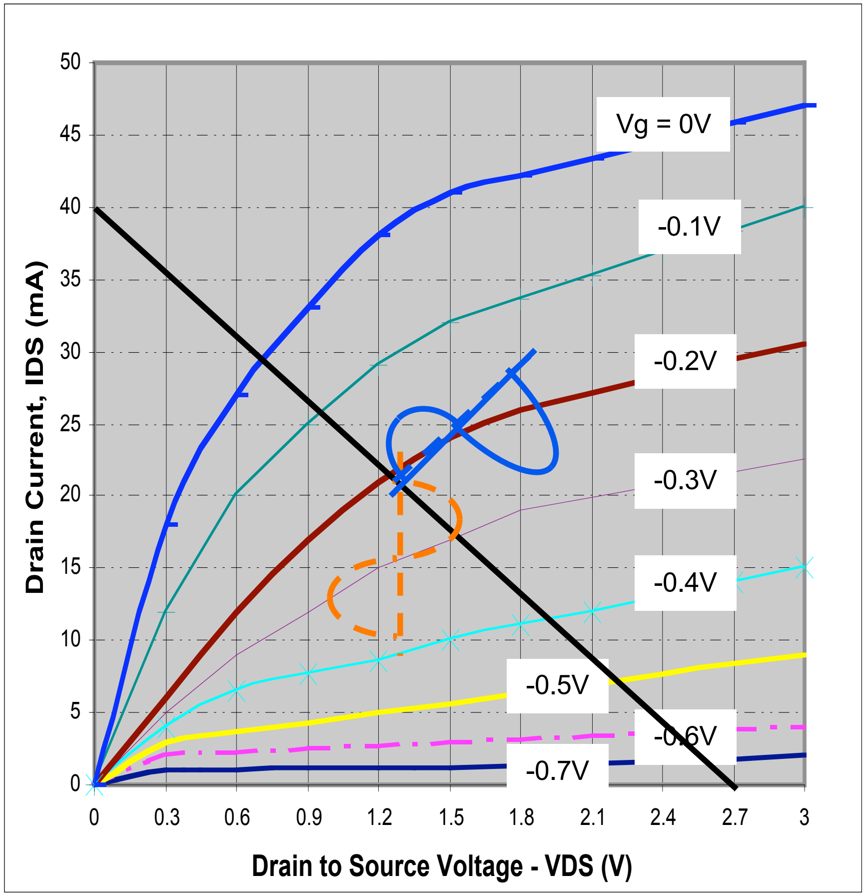
  Formal literature search & industry/university survey

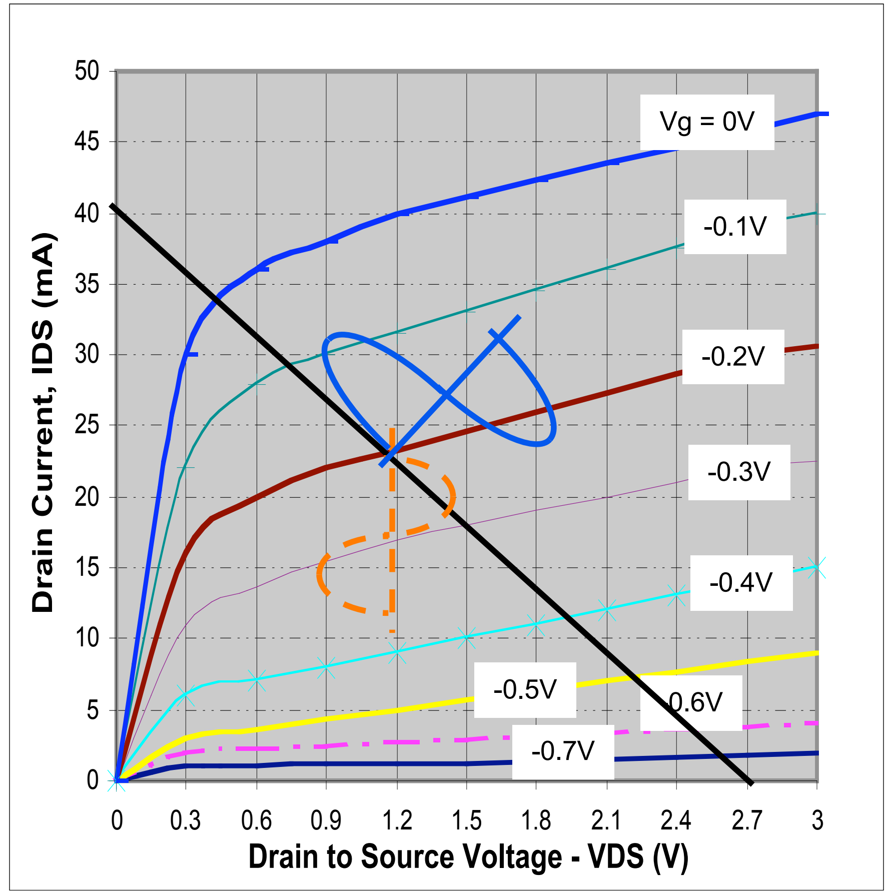
  Simulation and modeling

  Performance analysis

  Development program plan

Typical FET Characteristics





Poor, Immature Technology

shows waveform distortion

Near Ideal

shows symmetric amplification

Materials technology drives transistor characteristics and temperature stability

Presentation Outline

1.0 Introduction/Overview

2.0 Requirements Definition: Mission and Architectures

3.0 Formation Flying Technology Assessment

4.0 Communications Technology Assessment

–RF Communications Technology Assessment

–Optical Communications Technology Assessment

5.0 On Board Processing vs Communication Bandwidth Trade/ Information Systems (IS) Core Definition

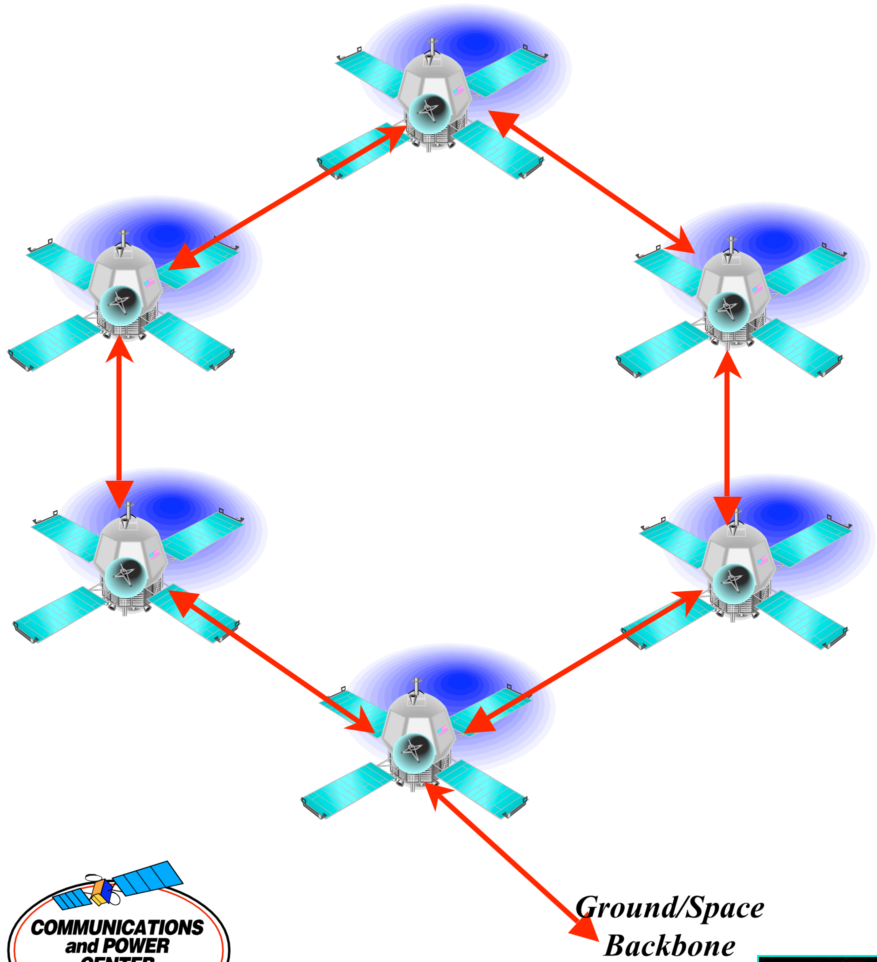
6.0 Integrated Technology Development Trades/Roadmaps

7.0 Summary, Recommendations & Phase 3

Leonardo "2015 and Beyond" Optical Communication Analysis (intra-cluster, LEO-GEO Relay)

Task 1.4 Optical Cross-link Assessment

Leonardo Intracluster Communication Link-Ring Topology



- *Ring Topology for Leonardo "2015" (6 S/C)*
- *Symmetric, bi-directional intracluster links (2 per S/C): Spacecraft can be identical*
- *Data transmitted (pipelined) through member S/C to "central" S/C for data distribution to ground user*
- *"Baseline" example for ISL raw data transfer requirements (271Mbps/instrument, 50% duty cycle)*
  - *real time: 3X raw data rate (813Mbps)*
  - *orbit average: 1.5X raw data rate (407Mbps)*
- *On Board Processed data rate- dependent on distributed processing connection bandwidth requirements*

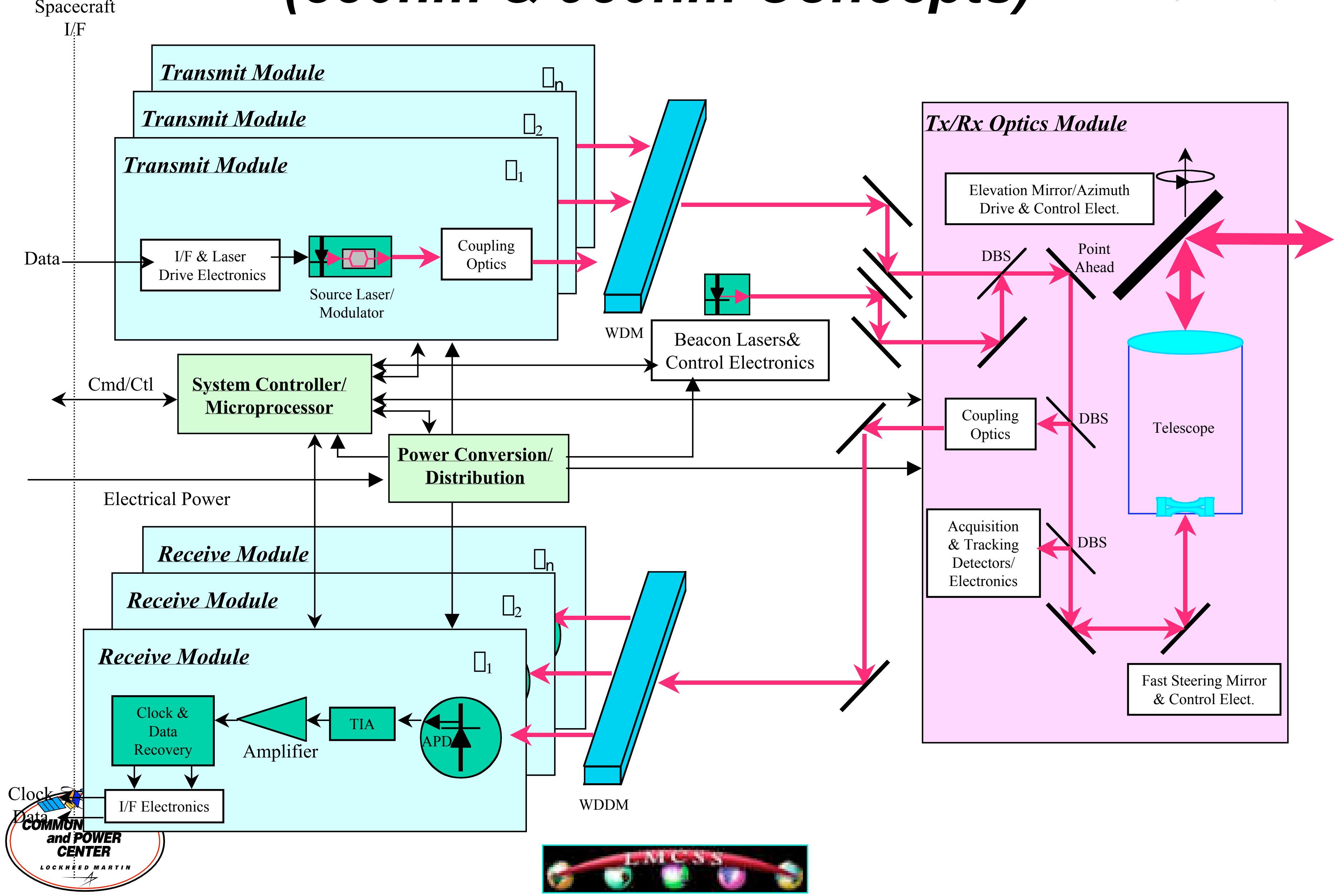
Optical ISL Intracluster Link Analysis

Optical ISL Link Spreadsheet for NRZ-OOK						
Transmit Wavelength	1550	nanometers				
Tx Laser Power (peak)	1.3900	Watts	1.43	dBW		
Solar Window	0.85		-0.71	dB		
WDM Beam Combiner Throughput	0.81		-0.92	dB		
Tx Telescope Gain (diameter)	8.00	cm	104.20	dB		
Tx Obscuration & Truncation Throughput	0.05	gamma	-0.93	dB		
Tx Optical Throughput (BOL)	0.70		-1.55	dB		
Tx Strehl Ratio	0.90		-0.46	dB		
Tx Pointing Loss	0.40		-3.98	dB		
Effective Tx EIRP	5.12E+09	Watts			97.1	dBW
Space Loss (range)	2000.00	kilometers			-264.2	dB
Rx Telescope Gain (diameter)	8.00	cm	104.20	dB		
Solar Window	0.85		-0.71	dB		
Rx Obscuration Throughput	0.90		-0.46	dB		
Rx Optical Throughput (BOL)	0.70		-1.55	dB		
WDDM Beam Separator Throughput	0.70		-1.55	dB		
NET Rx Gain					99.9	dB
Signal Strength at Detector (peak)	1.92E-07	Watts			-67.2	dBW
Link Path Transmission	1.00		0.00	dB		
Path Scintillation Effects	1.00		0.00	dB		
Required Photons per Bit(1)	120.00	1550.00				
Power Extinction Ratio	20.00					
Average Laser Power Out	0.7298	Watts				
Data Rate	2488.00	Mbps				
Required Signal Level (peak)	3.83E-08	Watts			-74.2	dBW
Electronic Implementation Loss (optical)			2.00	dB		
EOL Aging Margin (optical)			2.00	dB		
EOL Link Margin (optical)					3.00	dB

- ***Lasercom link spreadsheet Leonardo "2015" full duplex intracluster communication link (symmetric link)***
- ***Maximum link range of 2000Km (400Km S/C altitude)***
- ***Link analyses:***
  - ***–830nm technology (DL&APD)***
  - ***–980nm technology (DL&APD)***
  - ***–1550nm technology (EDFA optical PA, preamp, PIN PD receiver***
- ***Loss included for Tx/Rx optics, pointing, and EOL aging effects***
- ***OOK modulation receiver sensitivity for BER of 1e-9***

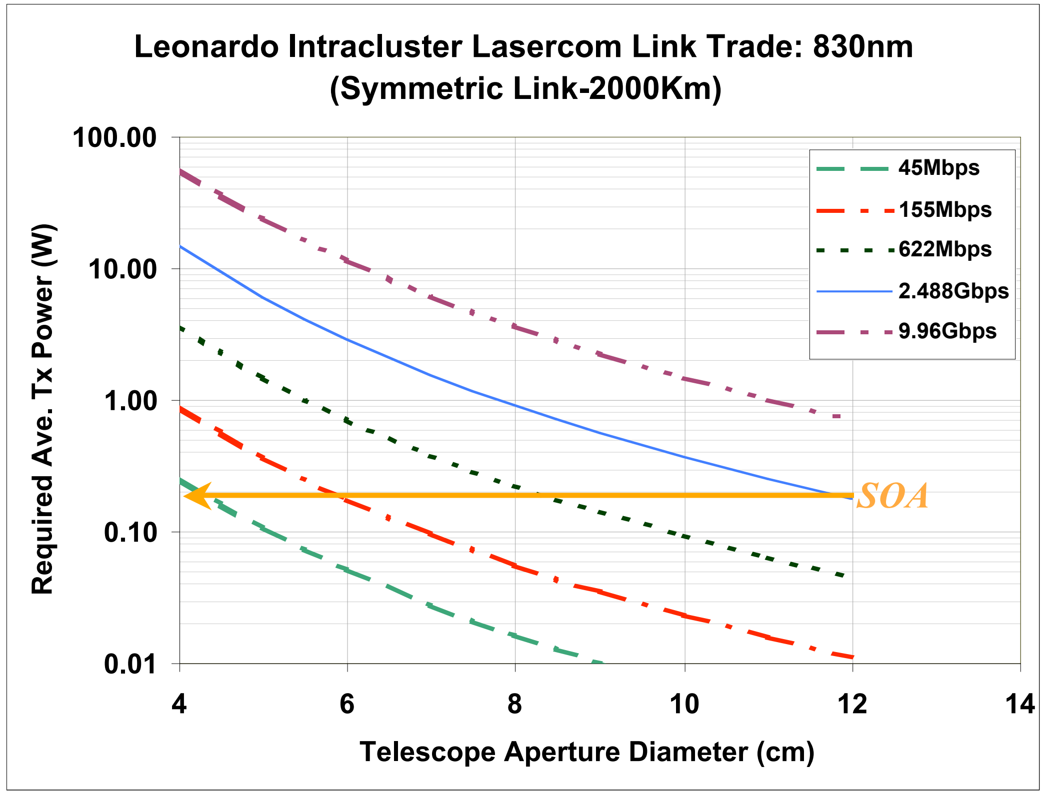
Link Spreadsheet Provides Estimate of Power/Aperture Required for Link Closure

Lasercom Terminal Block Diagram (830nm & 980nm Concepts)



Leonardo Intracluster Optical Link Trade (830nm Technology)

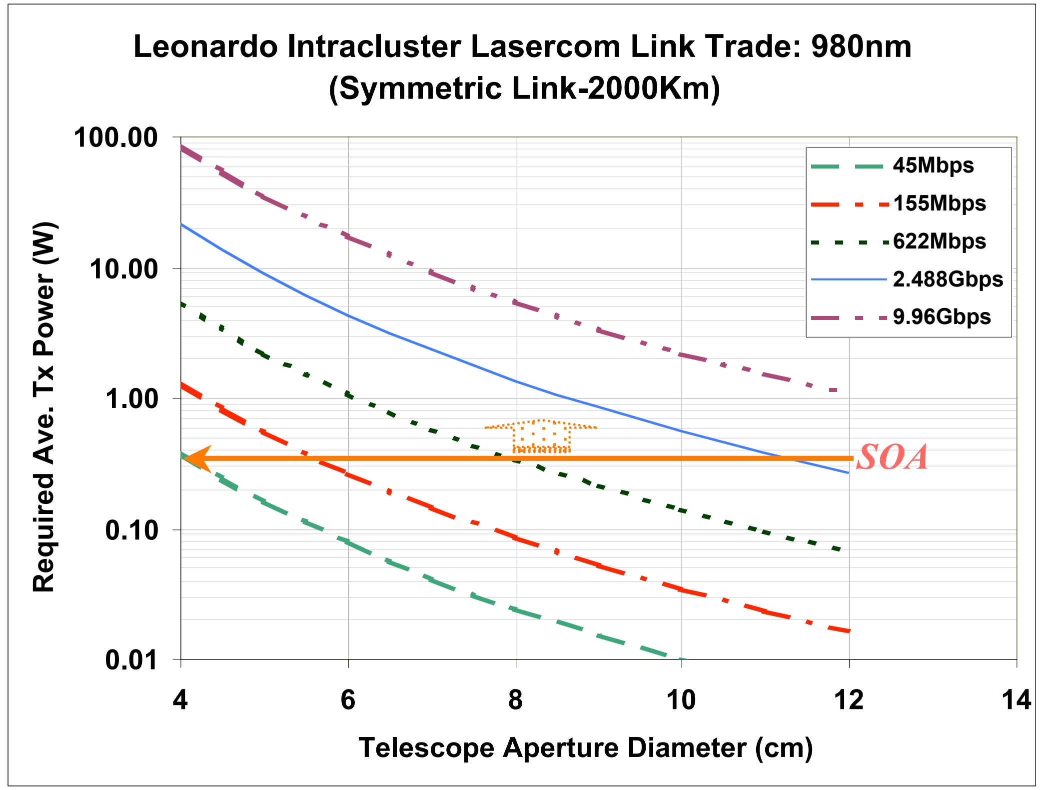
- *Crosslink maximum range: 2000km (farthest separation)*
- *830nm direct detection lasercom technology*
  - *–direct modulated diode laser*
  - *–Si APD detector*
- *Link Parameters(single channel):*
  - *–OOK modulation*
  - *–10^{-9} BER (275 photons/bit)*
  - *–3 dB EOL margin*
  - *–symmetric link (common Tx/Rx optics-identical terminals)*
- *Link trade: ave. Tx optical power vs telescope aperture size*
- *State-of-Art 830nm single mode diode technology: 200mW average optical power*



830nm Technology Capable for Lower Crosslink Data Rates

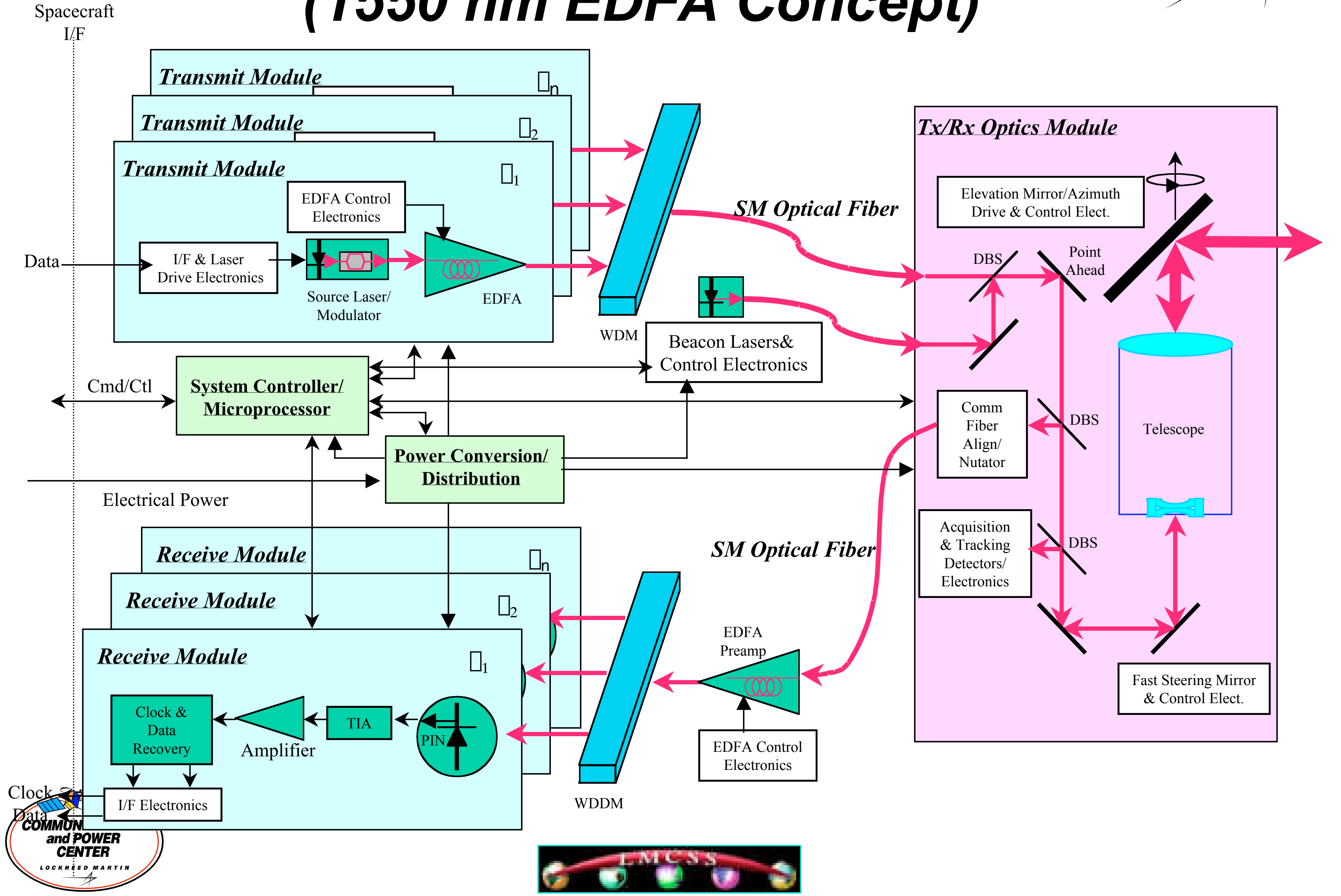
Leonardo Intracluster Optical Link Trade (980nm Technology)

- *Crosslink maximum range: 2000km (farthest separation)*
- *980nm direct detection lasercom technology (COTS EDFA pumps)*
  - *–direct modulated diode laser*
  - *–Si APD detector*
- *Link Parameters(single channel):*
  - *–OOK modulation*
  - *–10^{-9} BER (350 photons/bit)*
  - *–3 dB EOL margin*
  - *–symmetric link (common Tx/Rx optics-identical terminals)*
- *Link trade: ave. Tx optical power vs telescope aperture size*
- *State-of-Art 980nm single mode diode technology: 360mW average optical power*



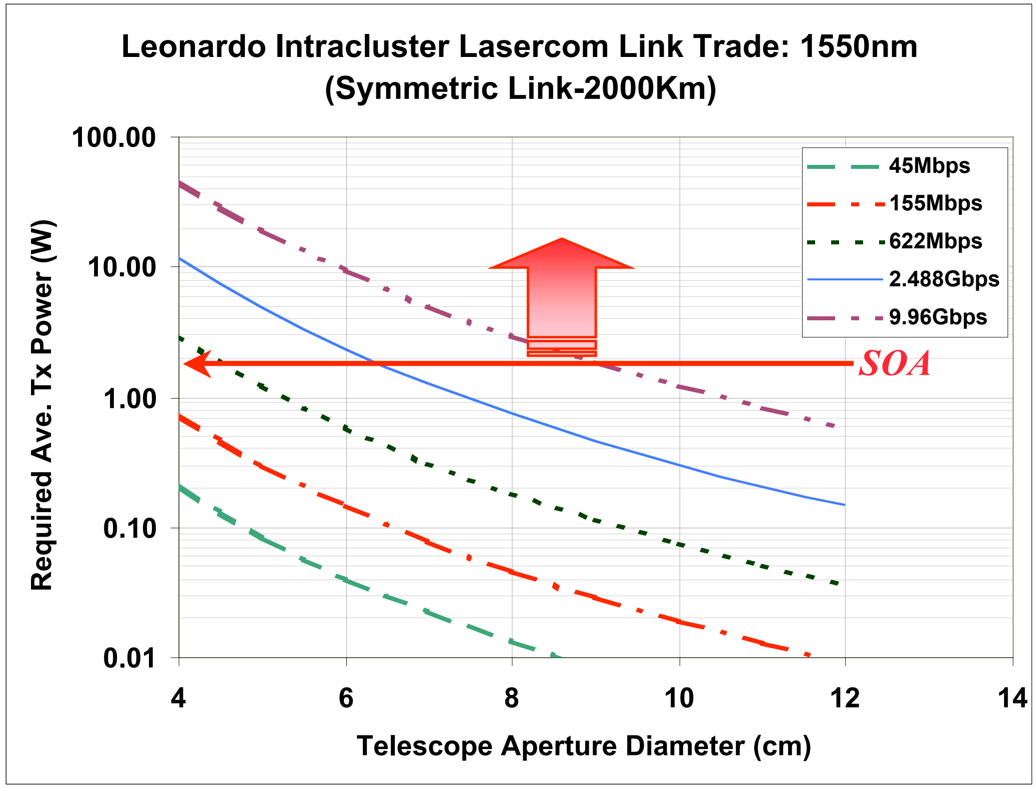
980nm Technology Capable for Low Data Rate Crosslinks - Some Growth due to Telcom Push

Lasercom Terminal Block Diagram (1550 nm EDFA Concept)



Leonardo Intracluster Optical Link Trade (1550nm)

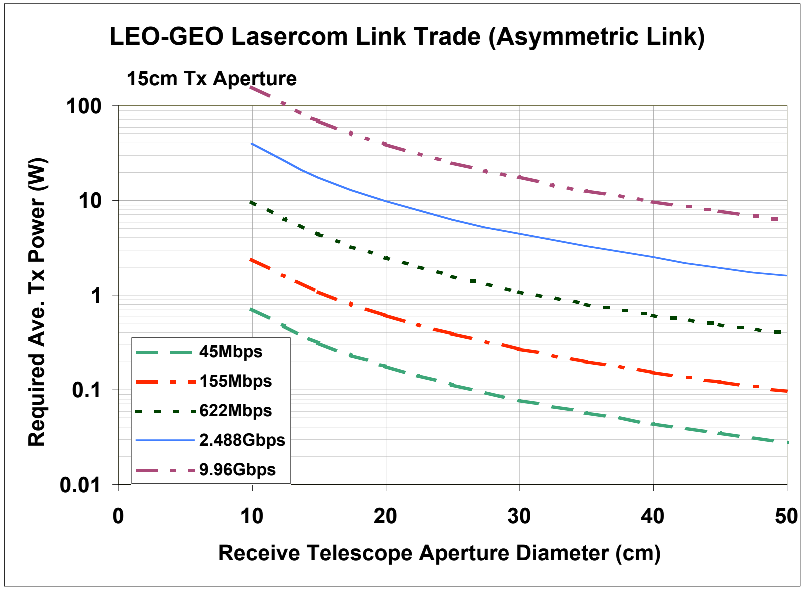
- ***Crosslink maximum range: 2000km (farthest separation)***
- ***1550nm direct detection lasercom technology***
  - *–laser/modulator & EDFA power amp*
  - *–PIN photodiode & EDFA preamp*
- ***Link Parameters(single channel):***
  - *–OOK modulation*
  - *–10^{-9} BER (120 photons/bit)*
  - *–3 dB EOL margin*
  - *–symmetric link (common Tx/Rx optics-identical teminals)*
- ***Link trade: ave. Tx optical power vs telescope aperture size***
- ***State-of-Art : Watt class EDFAs-> growth path to higher output optical power***

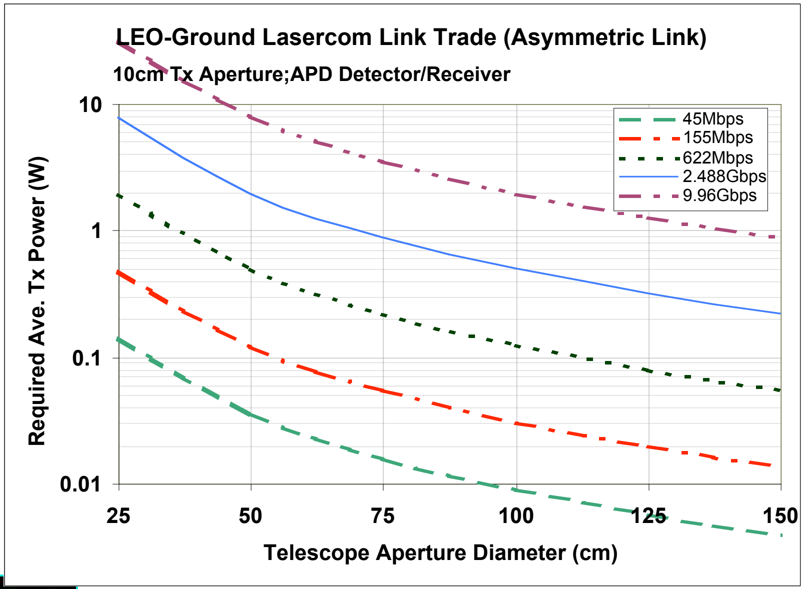


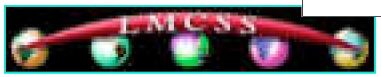
1550nm Technology Capable of High Crosslink Data Rates with Growth

Network Access Leonardo Optical Links

- *Leonardo Network Access Optical Links (LEO-GEO, LEO-Ground)*
  - *–1550nm EDFA lasercom terminal concept design*
  - *–NRZ-OOK modulation format*
  - *–APD receiver LEO-Ground*
  - *–EDFA optical preamp receiver:LEO-GEO*
  - *–10^{-9} BER (no coding); 3 dB EOL Margin*
- *Link Trade Summary from Phase 1*
  - *–LEO-GEO maximum link range: 43,000Km*
  - *–LEO-Ground maximum link range:1580Km*
    - *•atmospheric transmission and scintillation losses*
- *Tx power (ave) vs aperture diameter for various data rates (single wavelength)*

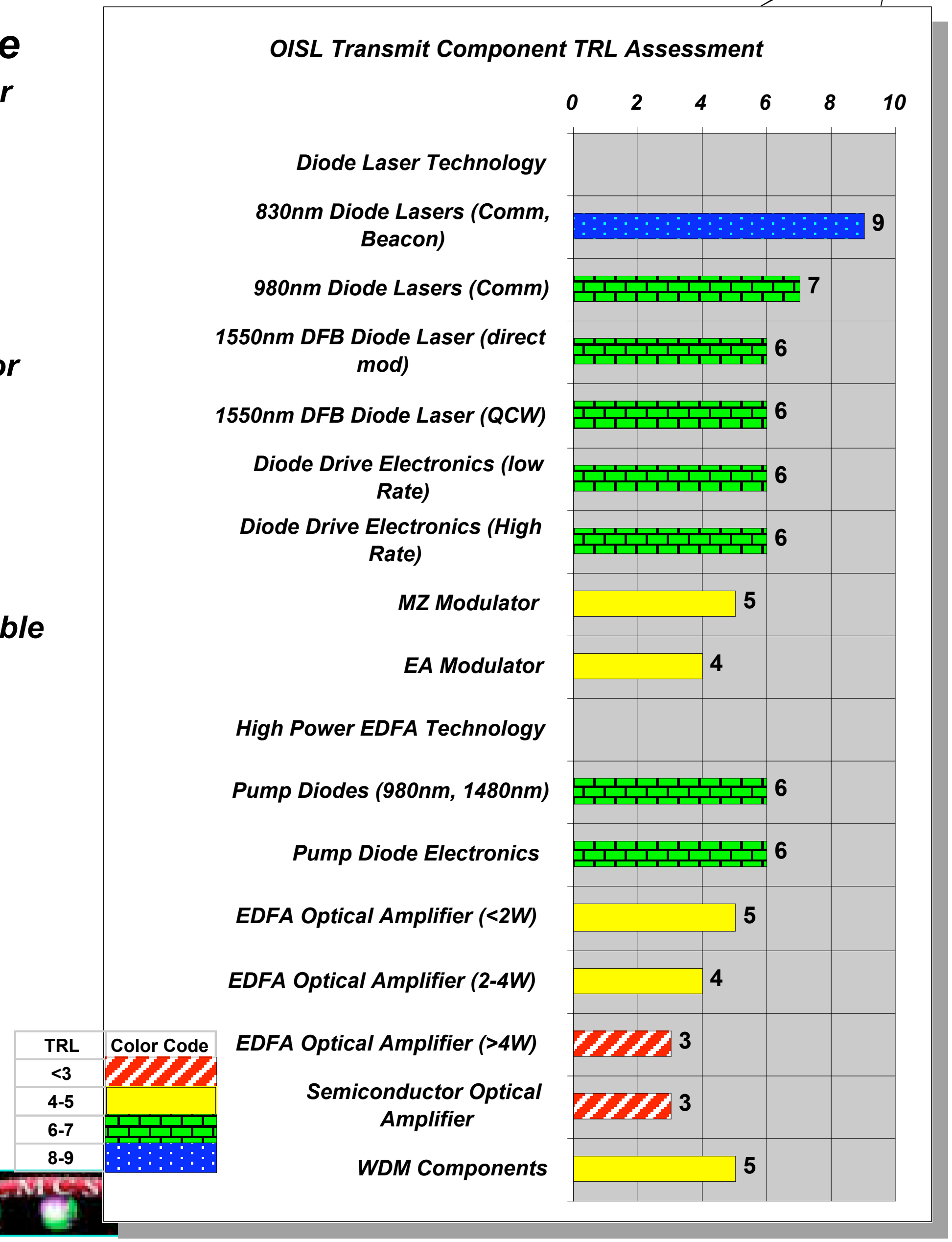






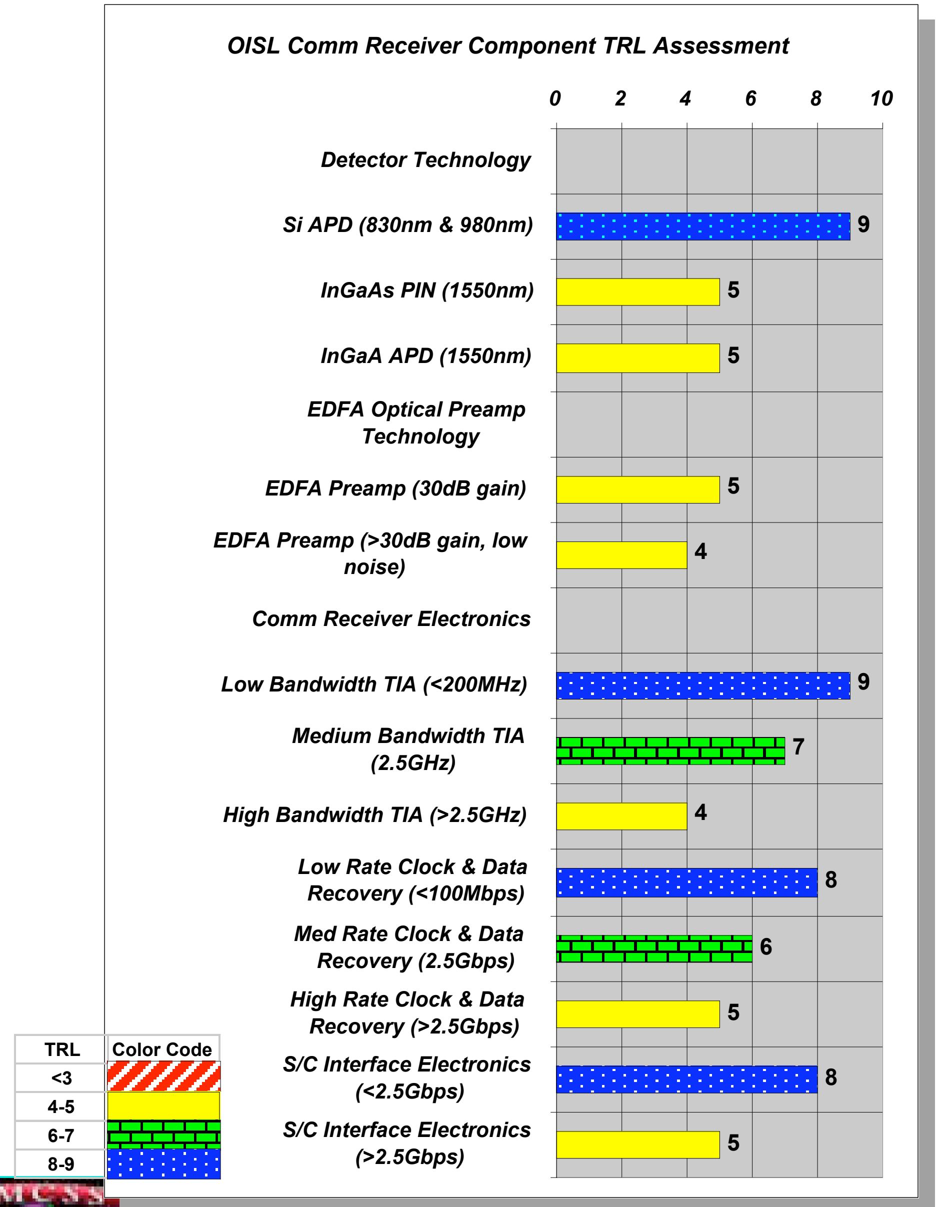
OISL TRL Assessment: Transmit Component Technologies

- ***Diode laser technology -flight heritage***
  - *–830nm diode laser: flight heritage for low power (SILEX, STRV, ETS-VI)*
  - *–980nm diode lasers: COTS ; up-screened*
  - *–1550nm diode laser : COTS; up-screened*
- ***External modulator technology- high data rates (>2.5Gbps)***
  - *–Mach-Zender, Electro-absorption Modulators for high bandwidth applications*
  - *–COTS components: up-screened*
- ***Optical amplifier technology***
  - *–EDFA; key enabling technology for terrestrial comm (long haul)*
    - *high power development-10W (COTS); scalable*
    - *key issues for space: radiation effects of Er+ doped fiber; packaging; reliability*
    - *low electrical efficiency: <10%*
  - *–Semiconductor Optical Amplifier (SOA)*
    - *advantages: small package, high efficiency (>40%)*
    - *high power, reliability issues*
- ***WDM Components***
  - *–pump; comm channels combine/split*



OISL TRL Assessment: Receiver Component Technology

- **Detector technologies**
  - –flight heritage for Si APD (SILEX, STRV, ETS-VI)
  - – InGaAs PIN photodiode (high bandwidth)
  - –InGaAs APD (higher gain, lower bandwidth)
- **Optical preamp technology**
  - –EDFA technology optimized for low noise
  - –higher gain, bandwidth in combination with PIN phtodiode
- **Receiver/interface electronics**
  - –low bandwidth TIA, clock & data recover flight heritage (SILEX, ETS-VI)
  - –medium bandwidth: COTS technology, up-screened for flight
  - –high bandwidth: COTS technology



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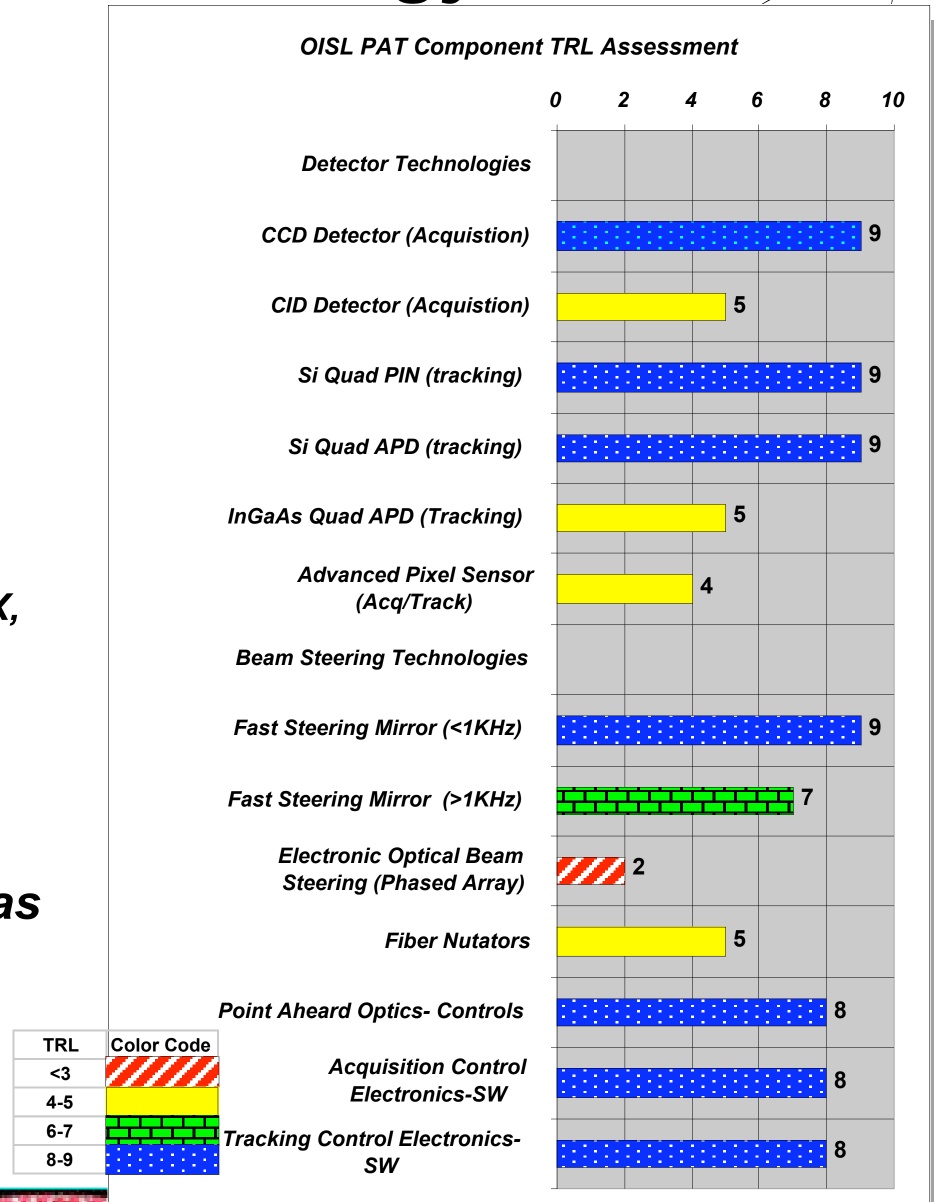
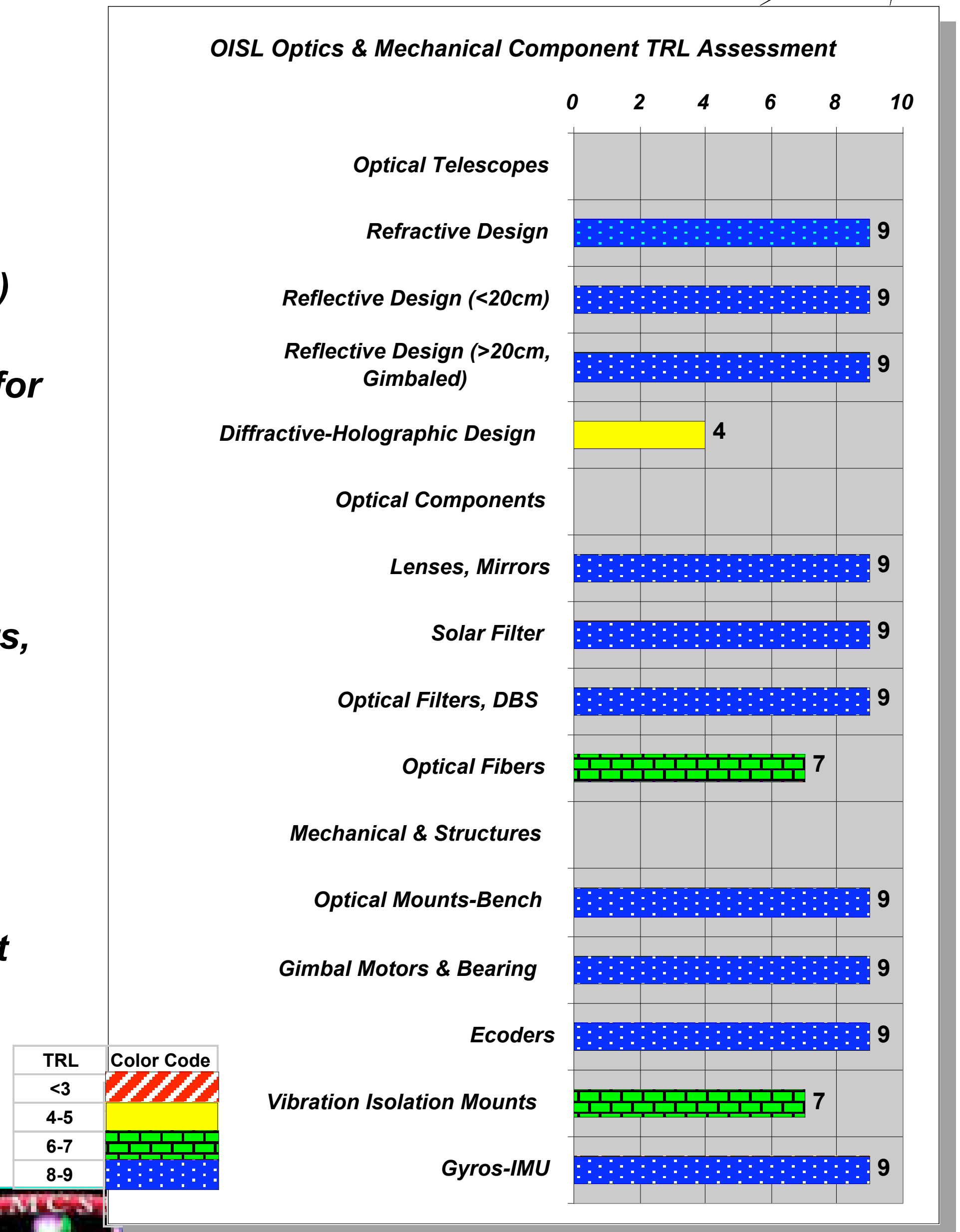
OISL TRL Assessment: PAT Component Technology

- **PAT detector technologies**
  - –flight heritage of CCD detectors (acquisition)
  - –flight heritage of Si QUAD APD for pointing/tracking feedback loop (SILEX, STRV, ETS-VI)
  - –InGaAs quad APD (1550nm)
  - –CID/APS 2D detectors
    - •windowing/subframing
    - •higher bandwidth (acq/track)
- **Beam steering technologies**
  - –fast steering mirror flight heritage (SILEX, ETS-VI, STRV)
  - –higher performance (>1KHz) available
  - –electronic beam steering (optical phase array): advantages- light weight, lower power, faster agility
- **PAT control hardware/software has flight heritage (SILEX, ETS VI, STRV)**



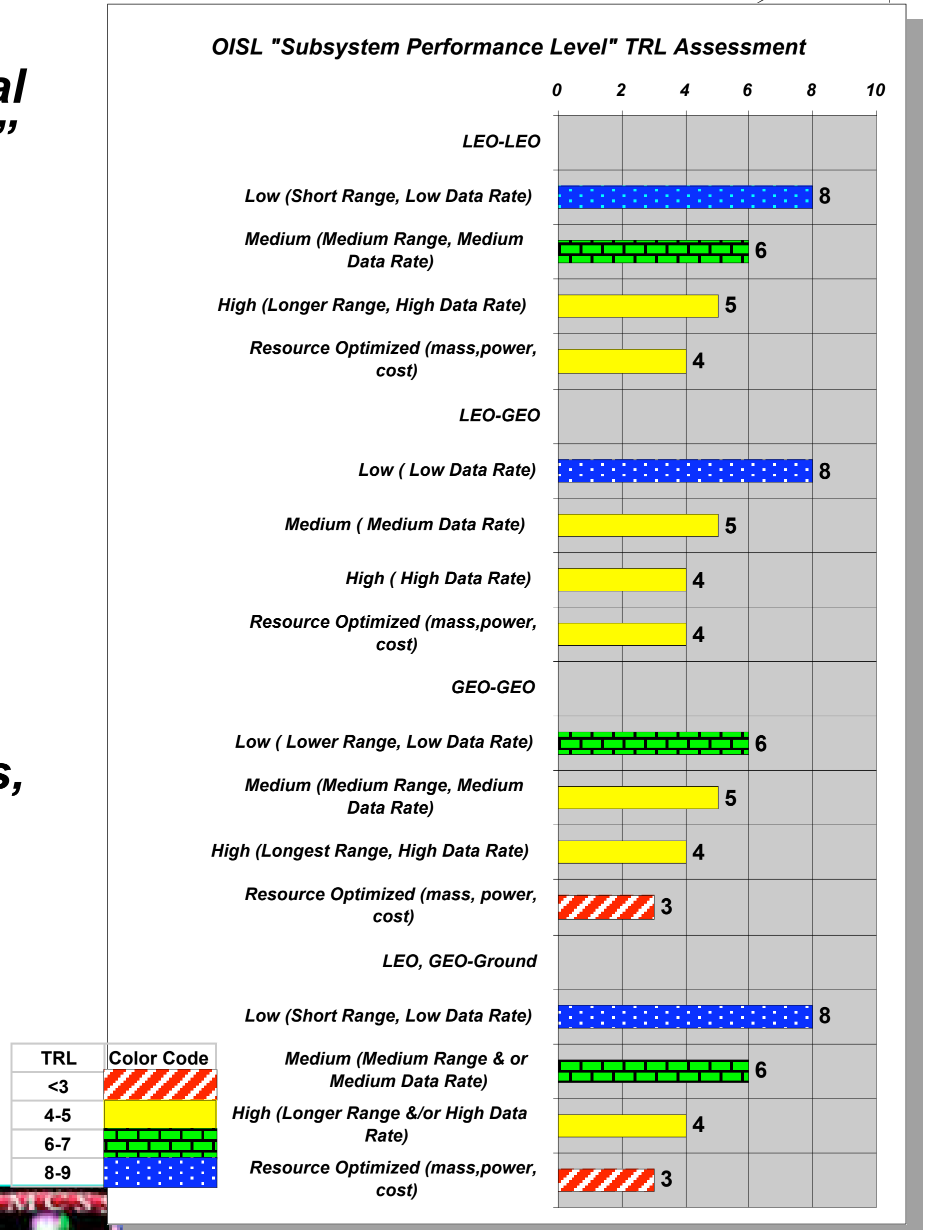
OISL TRL Assessment: Optical and Opto-Mechanical Component Technology

- *Optical Telescopes for OISL Applications*
  - –refractive/reflective telescope flight heritage (imaging sensors)
  - –gimbaled telescope flight heritage (HRDI)
  - –flight heritage for large optics (>20cm)
  - –diffractive/holographic optics: potential for lighter, cheaper components
- *Optical Components*
  - –extensive flight history for optical components (lenses, mirrors, beam splitters, filters, etc.) : optical instruments, sensors; OISL-SILEX, STRV,ETS-VI
- *Mechanical and Structural Components*
  - –optical mounts/bench flight heritage (optical instruments)
  - –gimbals, bearings, encoders, gyros flight heritage
  - –vibration isolation



OISL "Subsystem Level" TRL Assessment

- *Technology assessment of Optical ISL (OISL) at a "Subsystem Level" depends on performance requirements*
  - *3 performance categories:*
    - *low: short range &/or low rate (<50Mbps)*
    - *medium:medium range &/or medium rate (50Mbps-1Gbps)*
    - *high:longest range &/or high data rate (>1Gbps)*
  - *"resource optimized" category:*
    - *design optimized for low mass, power, size & cost*
- *Communication links for Earth Science (LEO-LEO, LEO-GEO, GEO-GEO, LEO/GEO-Ground)*



Key Technologies for Optical Intersatellite Communications

Component Technologies Level

- PAT technologies
  - high performance (sub microrad)
  - cost/performance
- Efficient, High Power Optical Amplifiers
- Wavelength Division Multiplexing (WDM)
- Non Mechanical Beam Steering
- Lightweight Optics (holographic/ diffractive)

"OISL Terminal" Level Development

- System Flight Demo
- "Resource" Optimized Systems
  - LEO-LEO (Teledesic)
  - Very Short Range/Resource Constrained (microsat,nanosat)
  - LEO-GEO; LEO/GEO-UAV
- Autonomous "Demand Access" OISL operations (RF hailing, signaling for access)
- Optical Communication Standard Rates

Section 5: On Board Processing vs Communications Bandwidth Trade/ Information System (IS) Core Definition

Jeff Sroga

Presentation Outline

1.0 Introduction/Overview

2.0 Requirements Definition: Mission and Architectures

3.0 Formation Flying Technology Assessment

4.0 Communications Technology Assessment

5.0 On Board Processing vs Communication Bandwidth Trade/ Information Systems (IS) Core Definition

6.0 Integrated Technology Development Trades/Roadmaps

7.0 Summary, Recommendations & Phase 3

On Board Processing vs Communications Bandwidth Trade Analysis

Task 1.6

Jeff Sroga

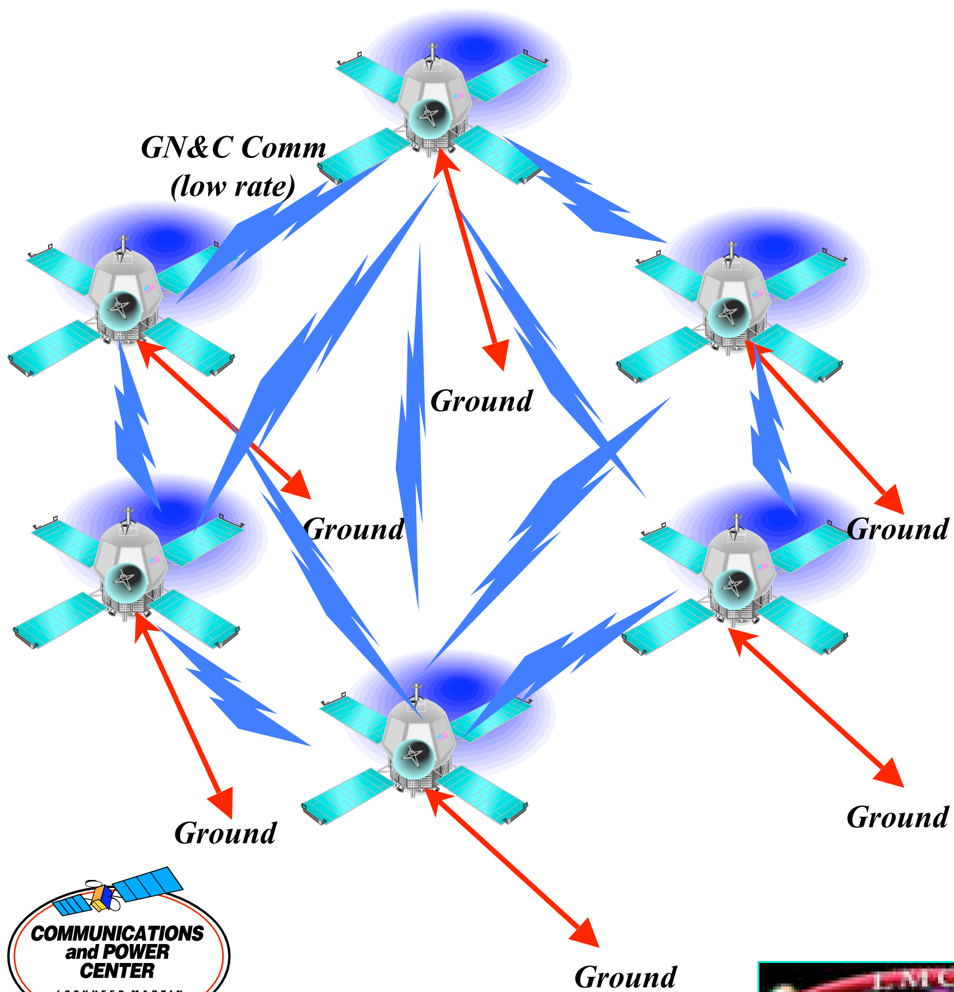
OBP vs Bandwidth Trade Overview

- ***Objective: Leonardo "2015" On Board Processing vs Communication Bandwidth Trade Space Evaluation***
- ***Approach:***
  - *select several data delivery schemes for Leonardo "2015" for raw and processed science data (3 options)*
  - *link analysis and S/C resource requirements for various communication links (intracluster, downlinks, LEO-GEO relay S/C) for raw and processed link data rates*
  - *estimate resource needs for OBP to reduce data rate (flight hardware, current SOA, and future hardware capabilities)*
  - *evaluate various delivery options in terms of S/C resource requirements*
- ***Communication Link technologies:***
  - *RF: Ka-band downlinks; Ka,V-band crosslinks- minimum power*
  - *Optical: 1550nm technology- growth path*

Trade Assumptions

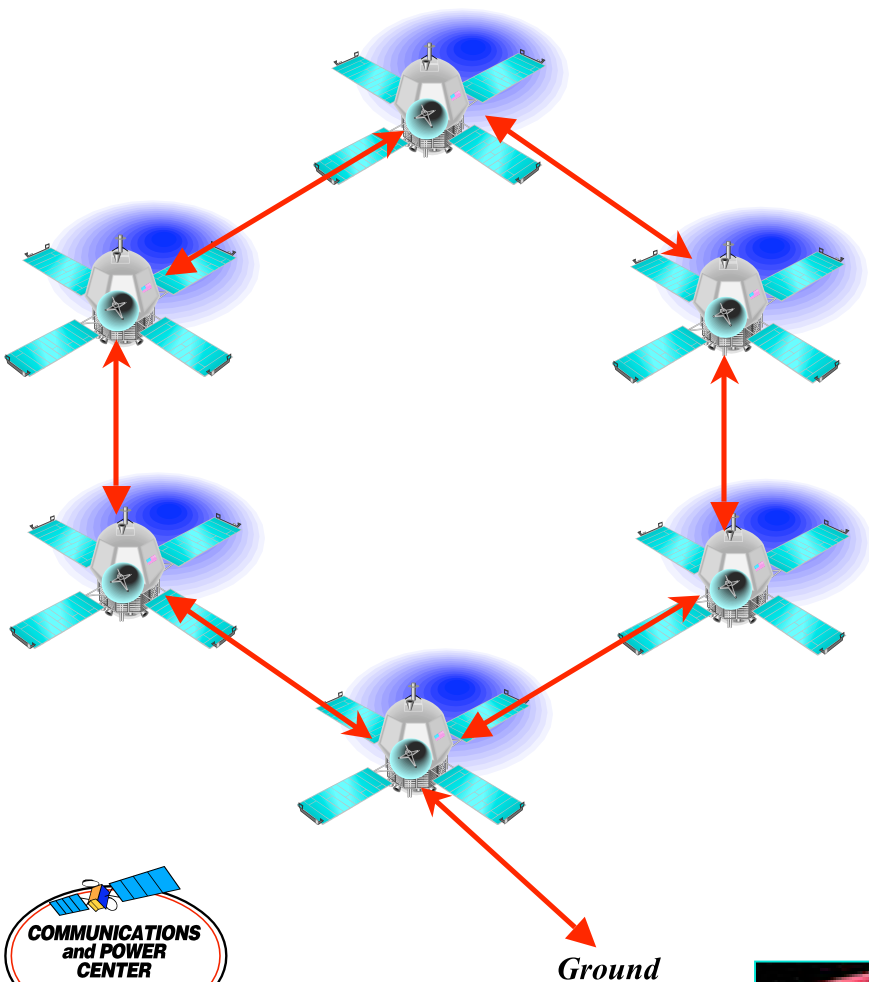
- Trade off at the Mission or S/C level
  - S/C resource (mass, power, cost) trade space
  - ROM estimates of resources for comm links (space-ground, intracluster, space-space) based on current or near term hardware concepts
  - ROM resource estimates for current flight processors- extrapolate to 10x processing increase for same resource allocation
  - ROM resource estimates for advanced processor concepts (FPGAs, ASICs)
  - assume "connection network" resources available
- Point design comm link concepts for Raw vs Processed Science data delivery (bounds)

OBP Trade Network Access Option 1: Individual S/C to Ground Station Contact



- ***Broadcast low rate GN&C communication links between formation S/C only (no science data)***
- ***Each S/C separately downlinks data to ground station (or multiple ground stations)***
- ***Raw data delivery ("send all bits")***
  - ***271Mbps instrument data rate; 50% duty cycle (daytime)***
  - ***RF: 1 GS contact/orbit per S/C (8minutes); required downlink rate: 1,567Mbps***
  - ***Optical: 1 GS contact/6 orbits per S/C (8 min.); required downlink rate: 9,411Mbps***
- ***Processed data delivery***
  - ***6.5Mbps "processed" instrument data rate; 50% duty cycle***
  - ***RF: 1 GS contact/orbit per S/C (8 minutes): required downlink rate: 38Mbps***
  - ***Optical: 1 GS contact/orbit per S/C (8 min.); required downlink data rate: 225Mbps***

OBP Trade Network Access Option 2: Central S/C to Ground Contact



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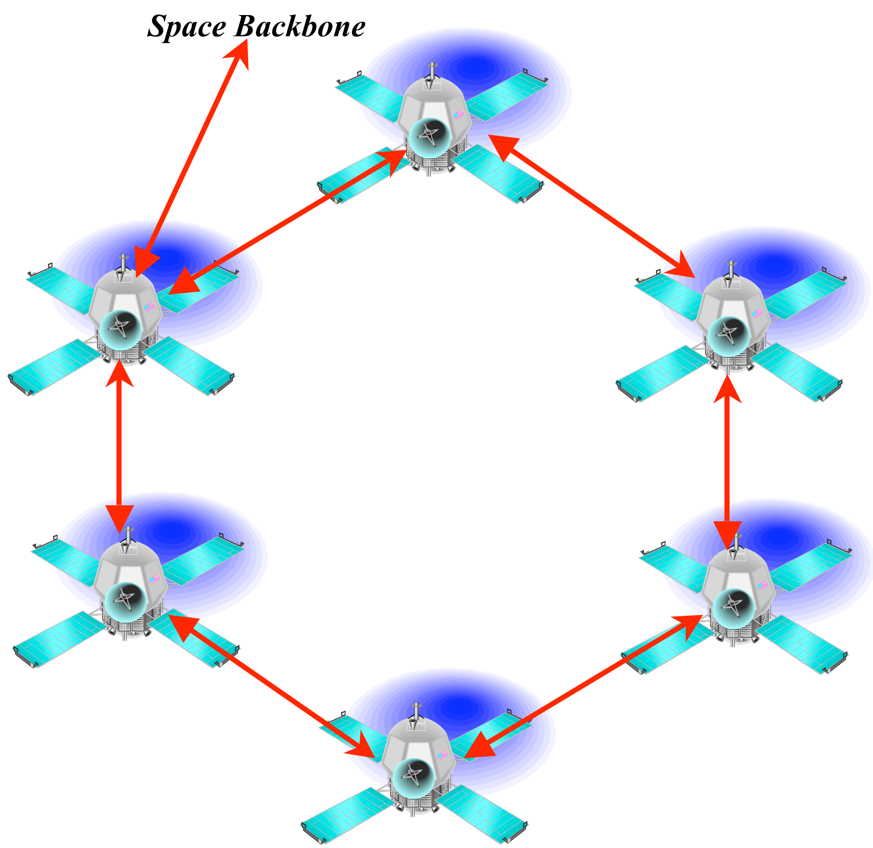
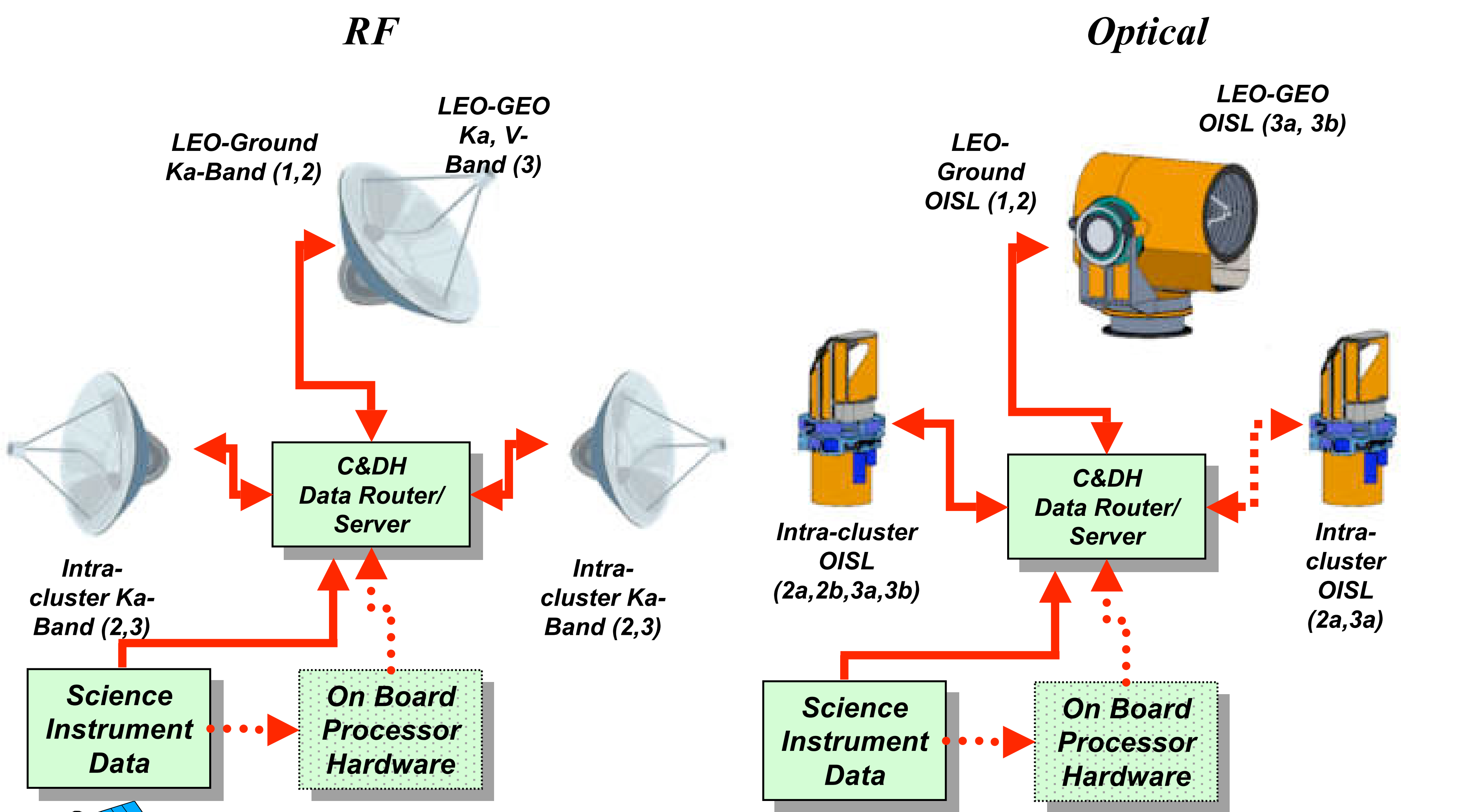
- *Data transmitted (pipelined) through member S/C to "central" S/C for data distribution to ground user (multiple ground stations)*
- *Raw data delivery ("send all bits")*
  - *–271Mbps instrument data rate; 50% duty cycle (daytime)*
  - *–Cross link required rate: 407Mbps (orbit average)*
  - *– RF: 2 GS contact/orbit (8minutes each); required down link rate: 4,706Mbps*
  - *–Optical: 1 GS contact/orbit (8 min.): required downlink rate: 9,411Mbps*
- *Processed data delivery*
  - *–6.5Mbps "processed" instrument data rate; 50% duty cycle*
  - *–Cross link required rate:10Mbps (orbit average)*
  - *–RF: 2 GS contact/orbit (8 min.); required down link rate: 113Mbps*
  - *–Optical: 1 GS contact/orbit (8min); required down link rate: 225Mbps*

OBP Trade Network Access Option 3: Central S/C to Space Backbone Contact



- Ring Topology for Leonardo "2015" (6 S/C)
- Symmetric, bi-directional intracluster links (2 per S/C): Spacecraft can be identical
- Data transmitted (pipelined) through member S/C to "central" S/C for data distribution to Space Backbone Network (SBS)
- Raw data delivery ("send all bits")
  - 271Mbps instrument data rate; 50% duty cycle (daytime)
  - Cross link required rate: 407Mbps (orbit average)
  - LEO-GEO Space Backbone: 30% orbit connected
  - required link rate: 2,712Mbps (max)
- Processed data delivery
  - 6.5Mbps "processed" instrument data rate; 50% duty cycle
  - Cross link required rate: 10Mbps (orbit average)
  - LEO-GEO Space Backbone: 30% orbit connected
  - required link rate: 65Mbps (max)
- Link rates for both RF and Optical ISL terminals

Communication Link Hardware Options



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RF Communication Links Hardware Summary

Trade Option	Link Type	Data Delivery Transfer	Data Rate (Mbps)	Max Link Range (Km)	EIRP dBW	Band	Antenna dia cm	Ampl Power dBW	Ampl Power W	Modul'r Type	Turbo Code rate	Terminal Mass (Kg)	Terminal Power (W)
1	LEO-Ground	Raw	1,567	1,000	43	Ka	65	3	2.00	16-QAM*	0.80	56.4	127
1	LEO-Ground	Processed	38	1,000	33	Ka	20	3	2.00	MSK	0.50	35.5	57
2	Intracluster	Raw	407	2,000	40	Ka	100	0	1.00	MSK	0.50	42.9	41
2	Intracluster	Raw	407	2,000	40	V	50	-7	0.20	MSK	0.50	36.8	48
2	Intracluster	Processed	10	2,000	32	Ka	30	0	1.00	MSK	0.50	35.4	40
2	Intracluster	Processed	10	2,000	32	V	20	-7	0.20	MSK	0.50	34.5	46
2	LEO-Ground	Raw	4,706	1,000	45	Ka	85	3	2.00	16-QAM**	0.80	57.7	127
2	LEO-Ground	Processed	113	1,000	36	Ka	30	3	2.00	MSK	0.50	36.4	57
3	Intracluster	Raw	407	2,000	40	Ka	100	0	1.00	MSK	0.50	42.9	41
3	Intracluster	Raw	407	2,000	40	V	50	-7	0.20	MSK	0.50	36.8	48
3	Intracluster	Processed	10	2,000	32	Ka	30	0	1.00	MSK	0.50	35.4	40
3	Intracluster	Processed	10	2,000	32	V	20	-7	0.20	MSK	0.50	34.5	48
3	LEO-GEO	Raw	2,712	43,000	70	V	150	13	20.0	BEM	0.50	73.6	189
3	LEO-GEO	Processed	65	43,000	53	Ka	85	13	20.0	MSK	0.50	57.1	109
3	LEO-GEO	Processed	65	43,000	53	V	100	0	1.00	MSK	0.50	45.0	53

Notes, comments

		0.015	0.005
Antenna gain	Ka-Band		V-Band
frequency	27 GHz	20 GHz	60
1.5 m dia	48	46	56
1 m dia	45	42	52
0.5 m dia	39	36	46
0.2 m dia	31	28	38
0.1 m dia	25	22	32

Parabolic antenna with gimbal steering
Antenn gain in dB (boresight) including tracking feed loss
Amplifier opeerated at saturation
Link margin is 3 dB with BER of 1e-9

* requires development of linear HPAs & LNAs
for non-constant envelope signals
requires 16-QAM to confine bandwidth within ITU allocation
also, code rate must be 0.8, not 0.5, as in other cases

** above note applies; however, RF bandwidth (>2400 MHz)
cannot be onfined to ITU requirements
requires > 10 bits/symbol (! !) or change in ITU allocations

Intersatellite Link Frequencies used in Trade

Optical Communication Links Summary

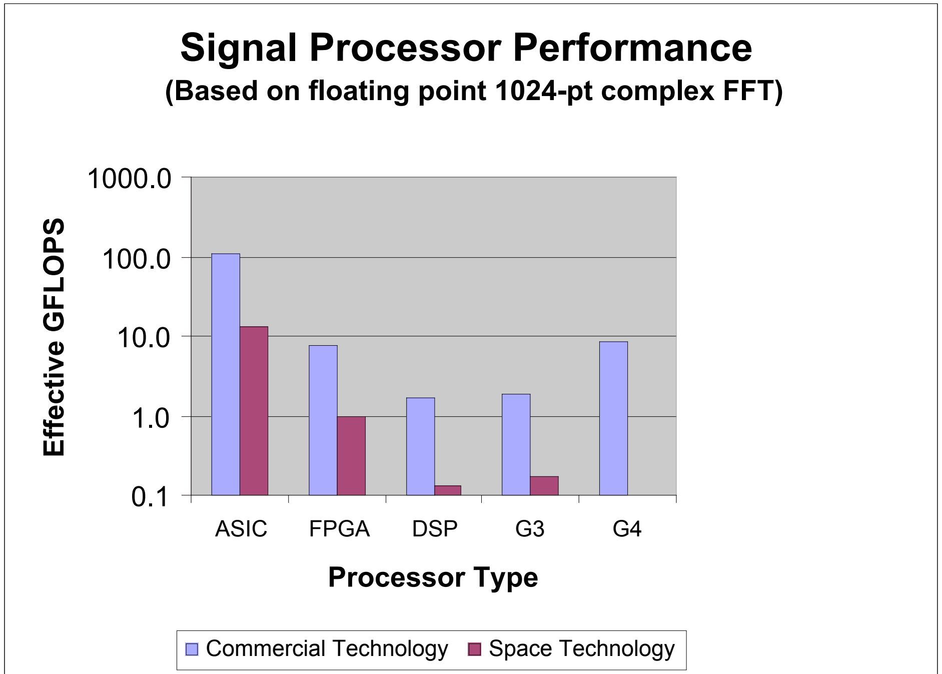
Trade Option	Link Type	Data Delivery Transfer	Data Rate (Mbps)	Max Link Range (Km)	Detection	Telescope Dia (cm)	Tx Ave. Power (W)	Terminal Mass (Kg)	Terminal Power (W)
1	LEO-Ground	Raw	9,411	1,000	DD-OOK	12.5	2	18	90
1	LEO-Ground	Processed	225	1,000	DD-OOK	8	0.1	16	65
2	Intracluster	Raw	407	2,000	DD-OOK	8	0.2	16	65
2	Intracluster	Processed	10	2,000	DD-OOK	6	0.15	10	30
2	LEO-Ground	Raw	9,411	1,000	DD-OOK	12.5	1	18	90
2	LEO-Ground	Processed	225	1,000	DD-OOK	8	0.05	16	65
3	Intracluster	Raw	407	2,000	DD-OOK	8	0.2	16	65
3	Intracluster	Processed	10	2,000	DD-OOK	6	0.15	10	30
3	LEO-GEO	Raw	2,712	43,000	DD-OOK	15	4	24	100
3	LEO-GEO	Processed	65	43,000	DD-OOK	12.5	0.16	16	70

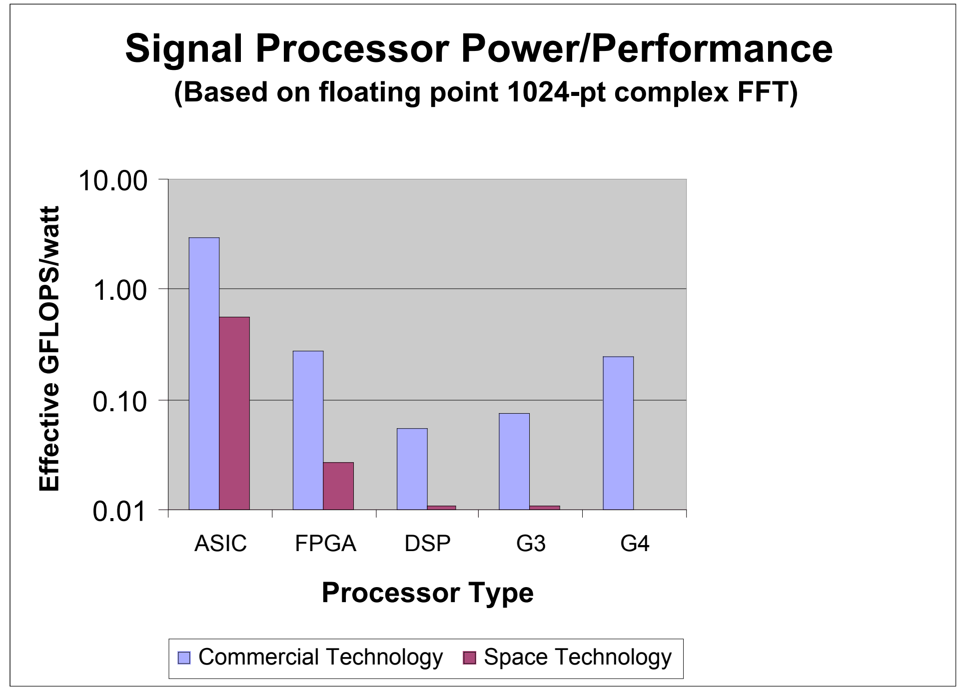
Notes, comments
1550nm Technology for all links
Link EOL margin is > 3 dB with BER of 1e-9 (no coding)
Ground Optical Terminal is 100cm dia (APD)
GEO Relay terminal is 30cm dia (EDFA preamp)
Intracluster Processed OISLs have APD receiver

Comparison of Signal Processor Technologies- Commercial and Space

Slide Courtesy of C. Alan Dennis at BAE Systems

BAE SYSTEMS





- **ASICs are the best performing technology; they are also the least programmable**
- **Each space technology is ~10x slower than the comparable commercial technology**
- **Space hardened versions of commercial designs are typically 100-200 Krads (Si)**
- **Re-configurable FPGAs are SEU soft, resulting in potentially unacceptable unavailability per year (e.g., in LEO, 950 km x 50°, the unavailability is ~1 minute)**
- **A hardened version of the G4 would be at least as good as re-configurable FPGAs**

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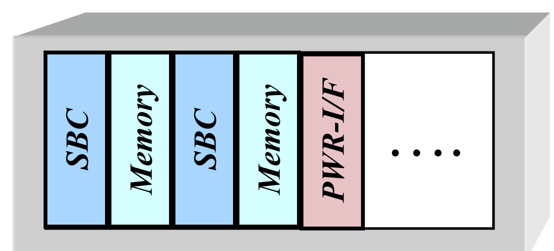
On Board Processing Hardware Trade Specifications

- On Board Processing Trade done at the S/C resource level
- On board processing hardware:
  - –single board computer (SBC); multiple copies for additional processing
  - –additional memory card/SBC for storage, programming, etc.
  - –additional card for power conditioning/ interface electronics (1 per 4 cards)
- Two levels of processor technology:
  - –RAD750: current SOA; ~10X processing increase over RAD6000, 1/2 size, mass
  - –What if "Advanced Processor": ~10X over RAD750; same size/power
- Advanced Processing Concepts: current FPGAs and ASICs technology for OBP
- Computer hardware scalable for on board processing needs

Rad Hard SBC Technology	Processing	Mass (Kg)	Power (W)	Comments
RAD 6000	35 MIPS	0.9	13	Flight Proven
RAD750	240 MIPS	0.55	12	Current SOA
Adv. Processor	2400 MIPS	0.55	12	10X RAD750 Performance
FPGA Processor	1 GFLOP	0.55	36	BAE Systems
ASIC Processor	16 GFLOPS	0.55	23	BAE Systems

Specs for Single Board Computer (SBC)



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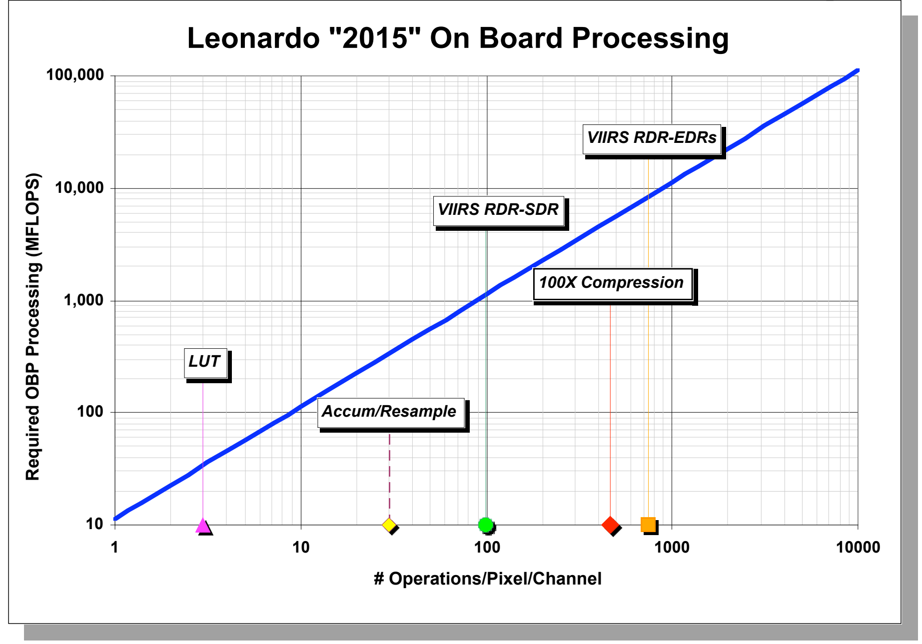
On Board Science Data Processing Needs/Requirements

MODIS		VIIRS (NPOESS)	
L1B Processing	1,299 MFLOPS	RDR->SDR Processing	550MFLOPS
L1-L4 Processing	5,739 MFLOPS	EDR Processing (46)	4,100 MFLOPS
Instrument Peak Data Rate	10.5Mbps	Instrument Peak Data Rate	10.5Mbps
Reference: http://spsosun.gsfc.nasa.gov/ETAS.html		Ref: LM NPOESS Phase 0 Study	

Leonardo “2015 and Beyond” Raw Data Rate: 271Mbps

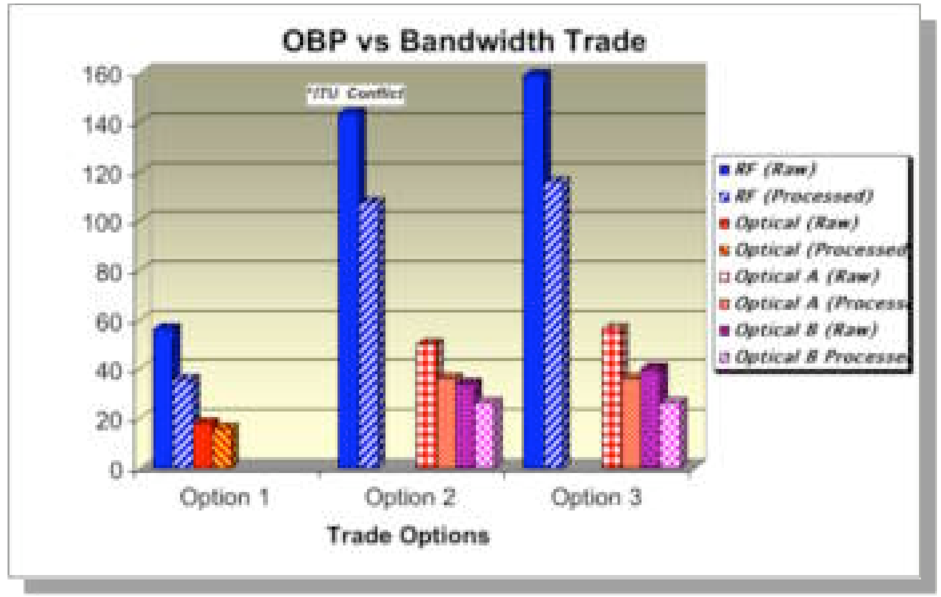
- ***# Processing steps from raw to end user (cal.,corrections, geo-location, cloud masks, etc.)***
- ***Science data processed at various levels***
  - ***–EOS: L0-L4***
  - ***–NPOESS:RDR->SDR->EDRs***
- ***Operational Instruments: MODIS (EOS); VIIRS (NPOESS)-10.5Mbps data rate (max)***
- ***Leonardo “2015”: >25X increase data rate***

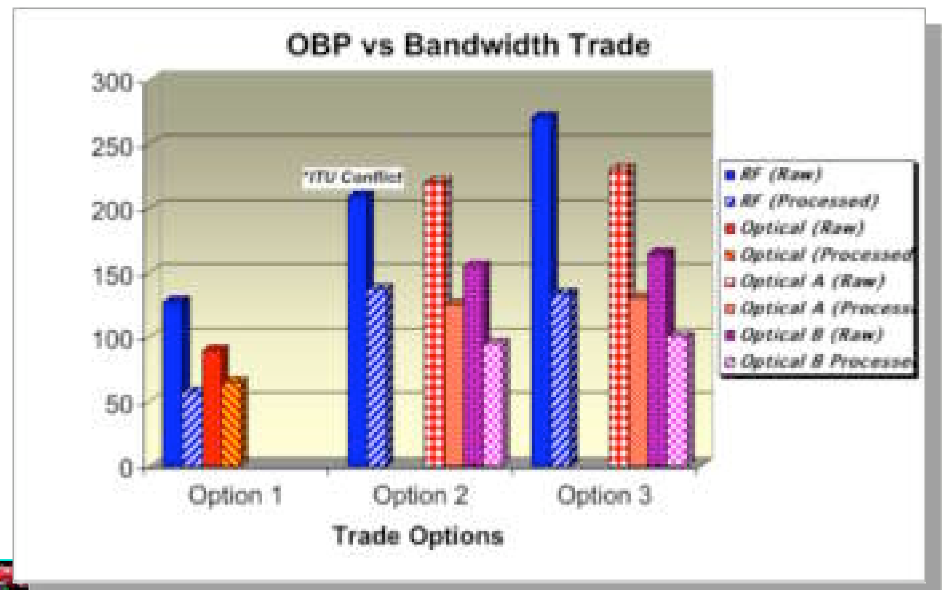


End User Science Data Processing Needs will Drive OBP Requirements

Communications Hardware S/C Mass/Power Resource Summary

- *Communication hardware mass & power resource requirements at S/C level for 3 options*
  - *–raw data transfer*
  - *–processed data transfer*
- *RF Comm hardware:*
  - *–parabolic dish for highest EIRP efficiency (electrical power)*
  - *–LEO-ground: Ka-band parabolic dish with gimbal steering (downlink bandwidth)*
  - *–space-space: 2 V-band parabolic dish with gimbal steering (crosslink bandwidth)*
- *Optical Comm hardware*
  - *–1550nm technology (space-ground, space-space)*
  - *–B case for Options 2,3- 1 OISL terminal for intracluster, 1 OISL terminal for network connection- intracluster (mass/power savings)*





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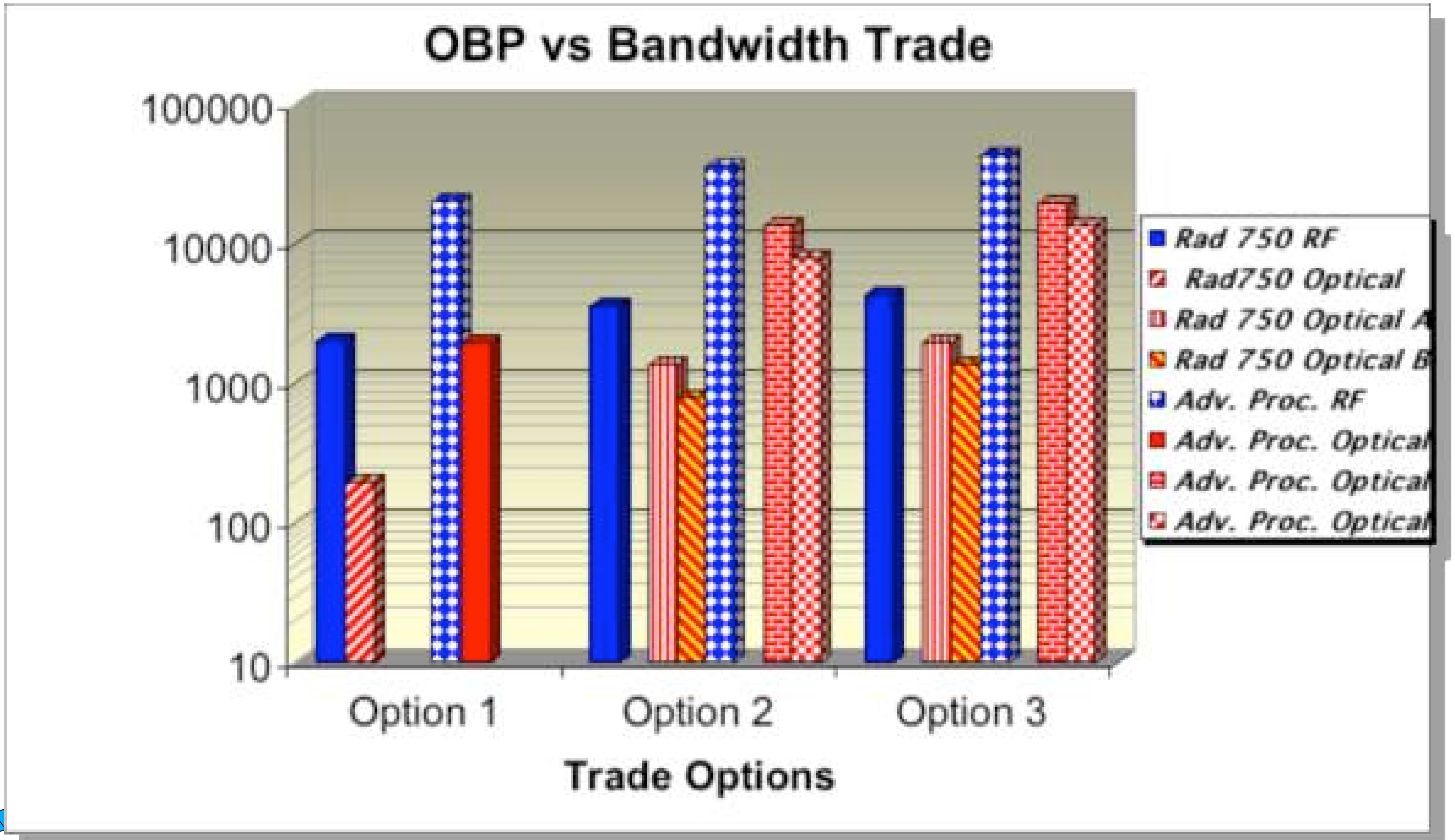
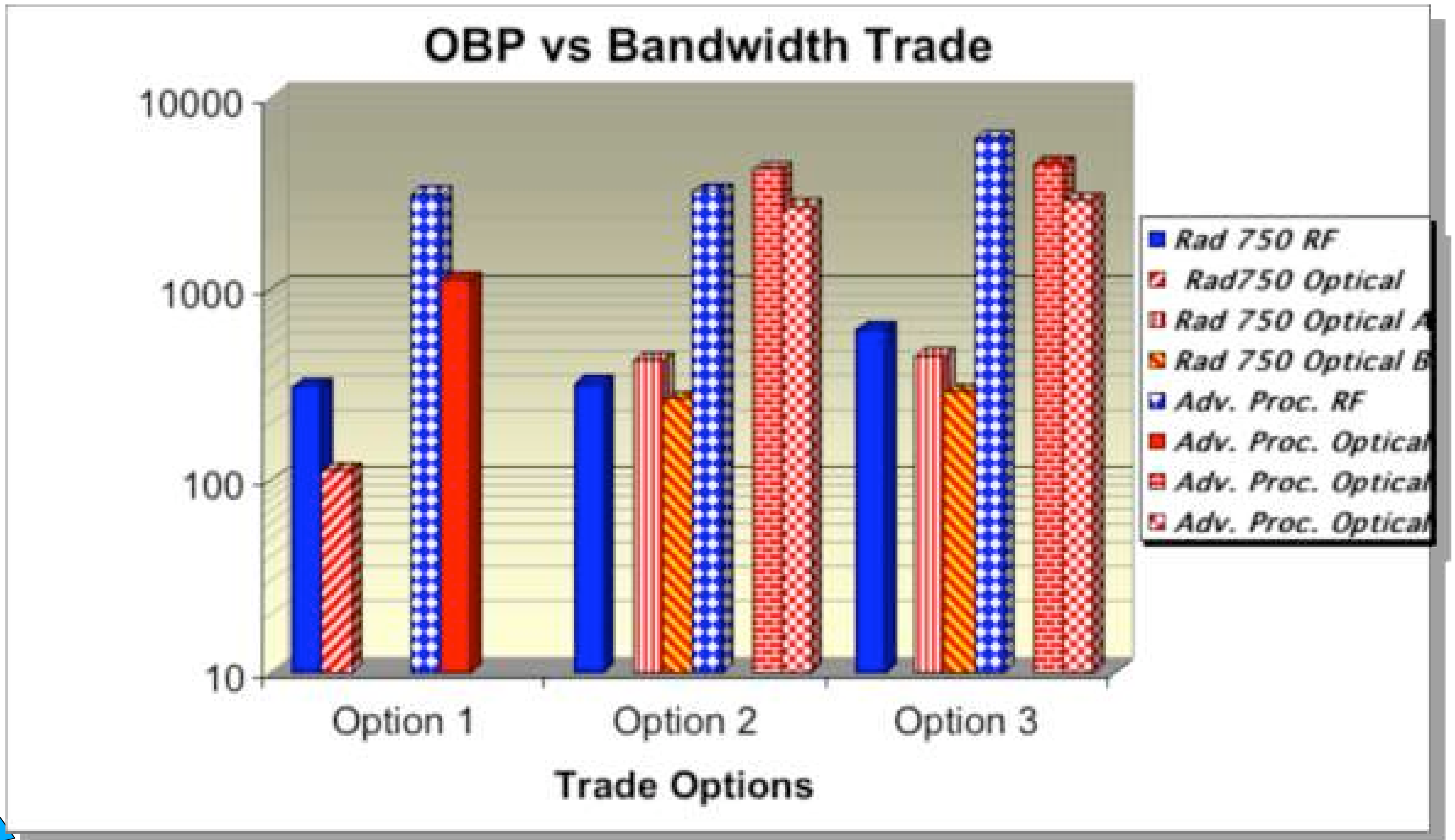
Processor "Mass Breakeven" Assessment

- *Processor "Mass Breakeven" point: Capacity of OBP hardware where "processor mass + processed comm hardware mass" = comm hardware mass for raw data transfer*



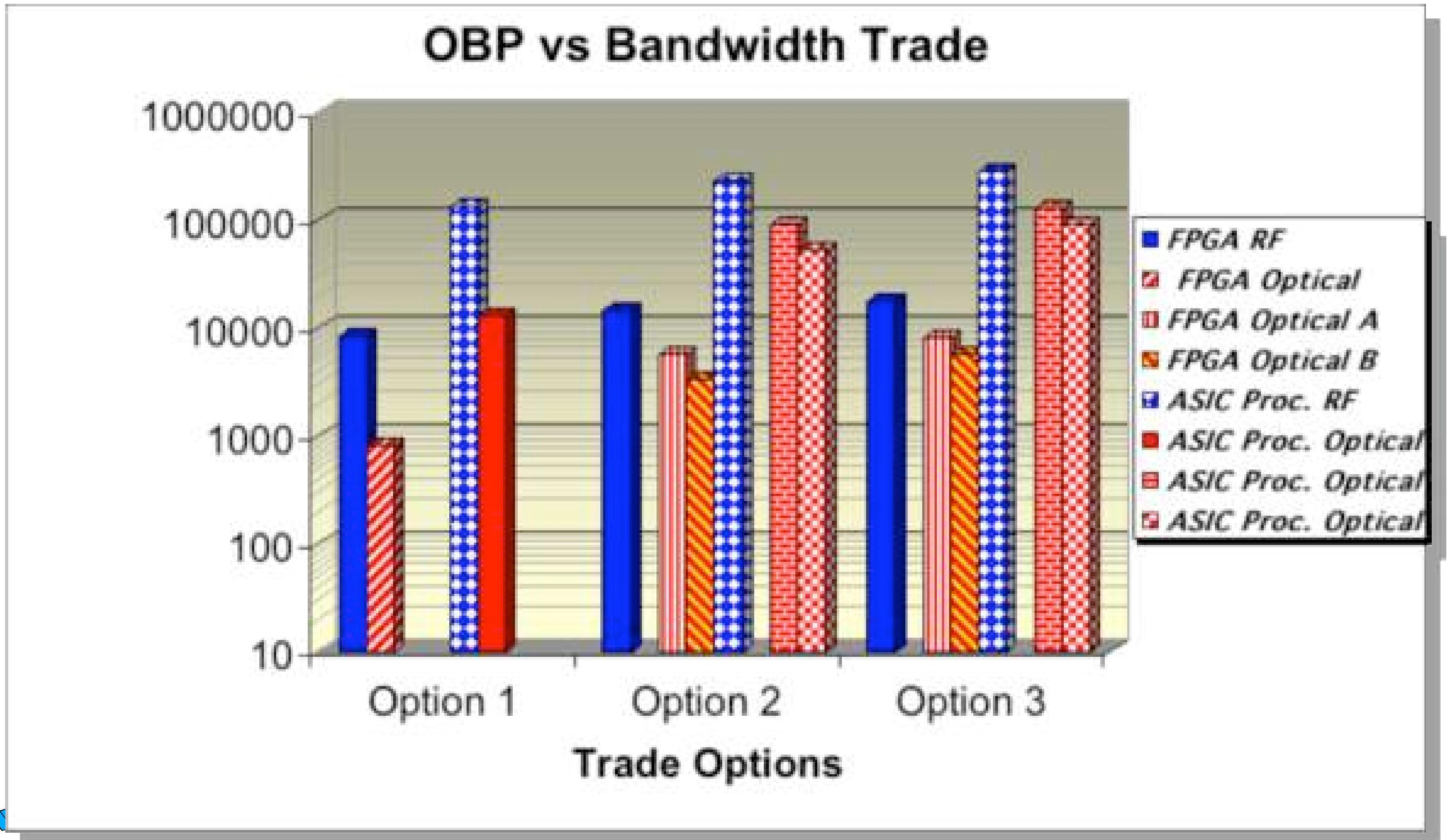
Processor "Power Breakeven" Assessment

- Processor "Power Breakeven" point: Capacity of OBP hardware where "processor power + processed comm hardware power" = comm hardware power for raw data transfer



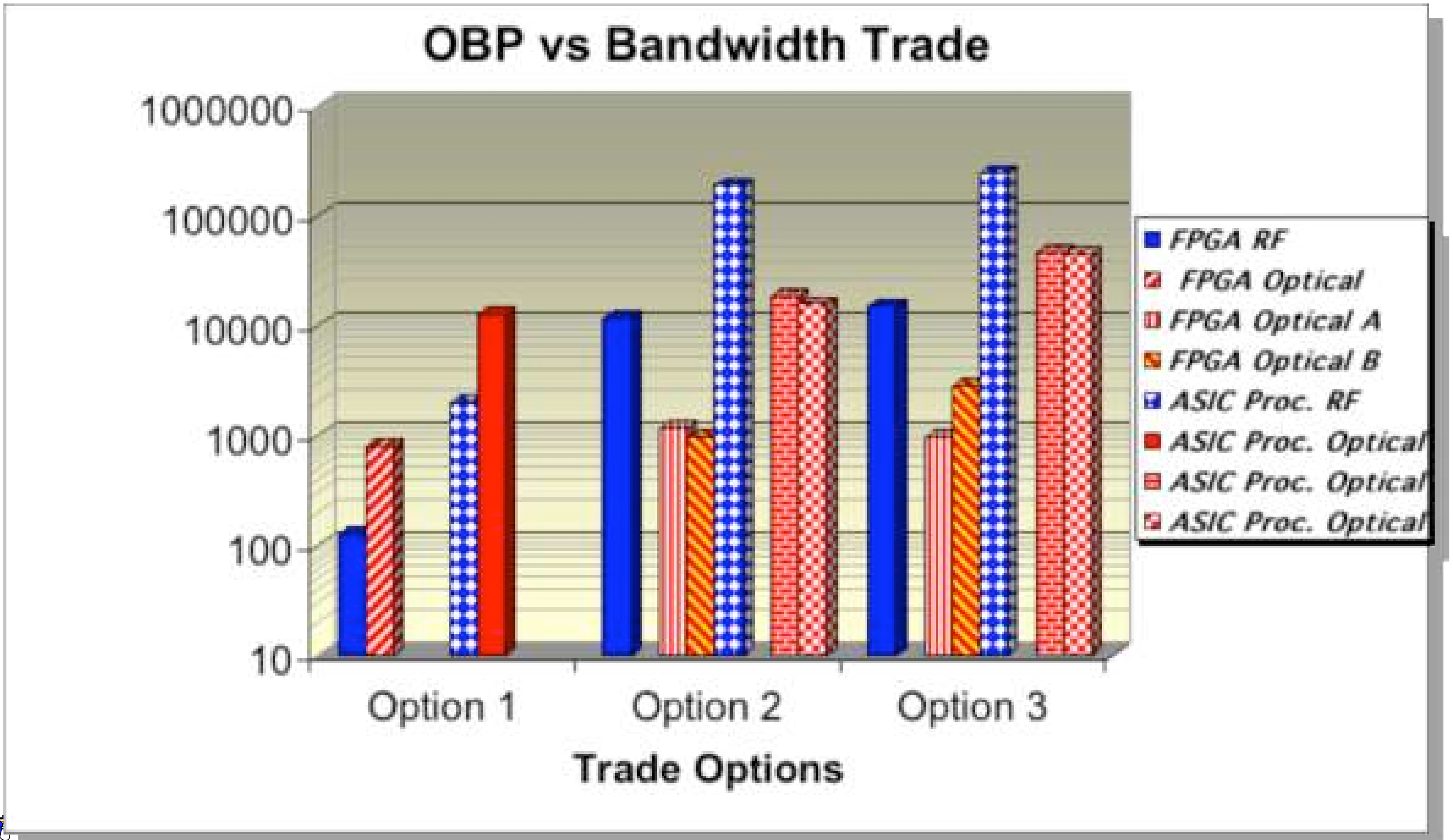
FPGA, ASIC Processor "Mass Breakeven" Assessment

- *FPGA & ASIC Processor "Mass Breakeven" point: Capacity of OBP hardware where "processor mass+ processed comm hardware mass" = comm hardware mass for raw data transfer*

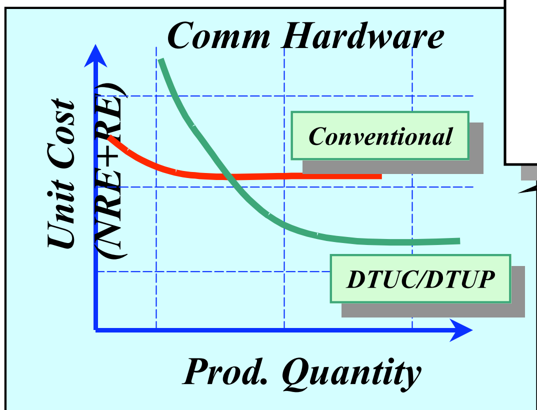


FPGA, ASIC Processor "Power Breakeven" Assessment

- ***FPGA & ASIC Processor "Power Breakeven" point: Capacity of OBP hardware where "processor power + processed comm hardware power" = comm hardware power for raw data transfer***

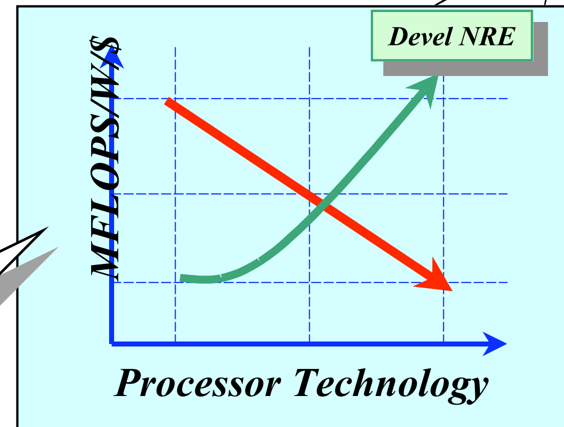


OBP vs Bandwidth Cost Trade/Issues

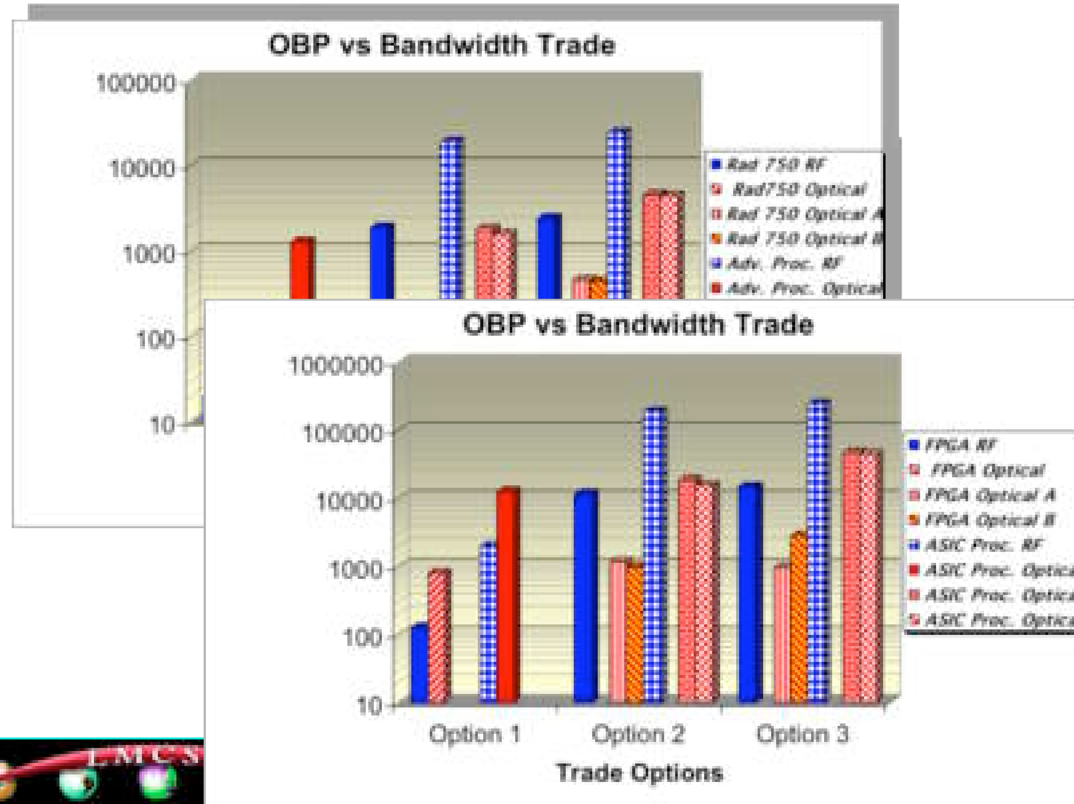


Comm Hardware Cost depends on Quantity, Mfg. approach

Processor Metric Generation Improvement-> NRE $$$



- ROM Cost Trade (RE costs only)
- Comm Hardware (RF & Optical)
- Processor Technology (CPU, FPGA, ASIC)
- Processor "Cost Breakeven"



Valid Cost Trade Requires Higher Fidelity Cost Details/ Ground Rules

OBP-Comm Bandwidth Trade Conclusions

- ***Example OBP Requirement: 100X compression (5GFLOPS requirement)***
  - ***current processor SOA (RAD750): OBP requires higher mass/ power for all Leonardo "2015" options ("Power Breakeven" more than 10-20X smaller than 5 GFLOPS)***
  - ***Advanced Processor (10X RAD750): OBP power nearly comparable ("Power Breakeven" within factor of ~2X of 5 GFLOPS)***
  - ***current gen FPGA processor: similar to 10X RAD750 performance (70%)***
  - ***ASIC processor: OBP advantage for all options***
- ***Mass advantages for OBP***
- ***Increased comm resources required from Option 1 to Option 2 to Option 3***
- ***Optical comm has mass/power advantages for options***
- ***Development of advanced processor concepts to improve performance metric (GFLOPS/Watt/K$) would benefit Leonardo "2015" mission***

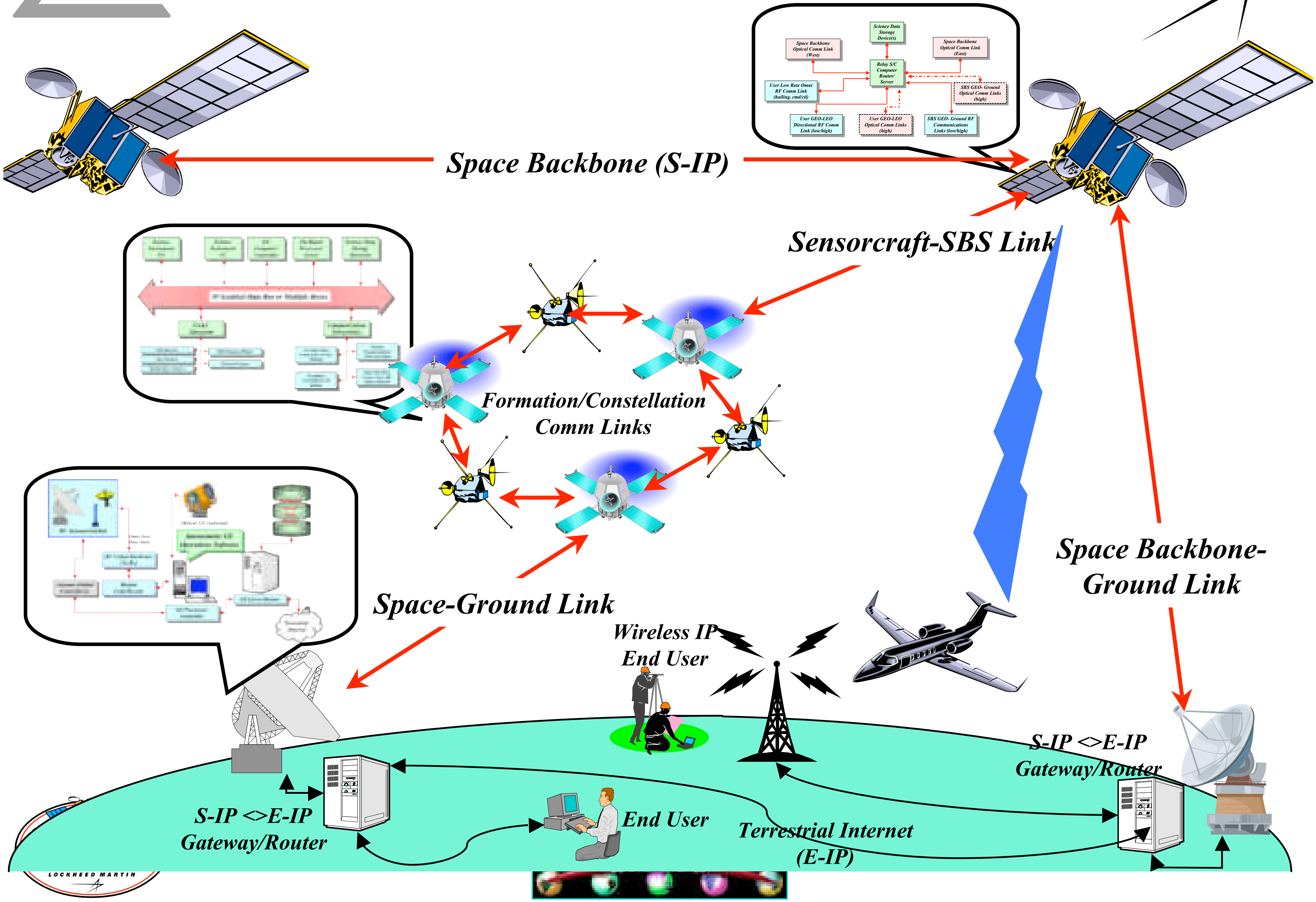
Information System (IS) Core Definition

Task 1.7

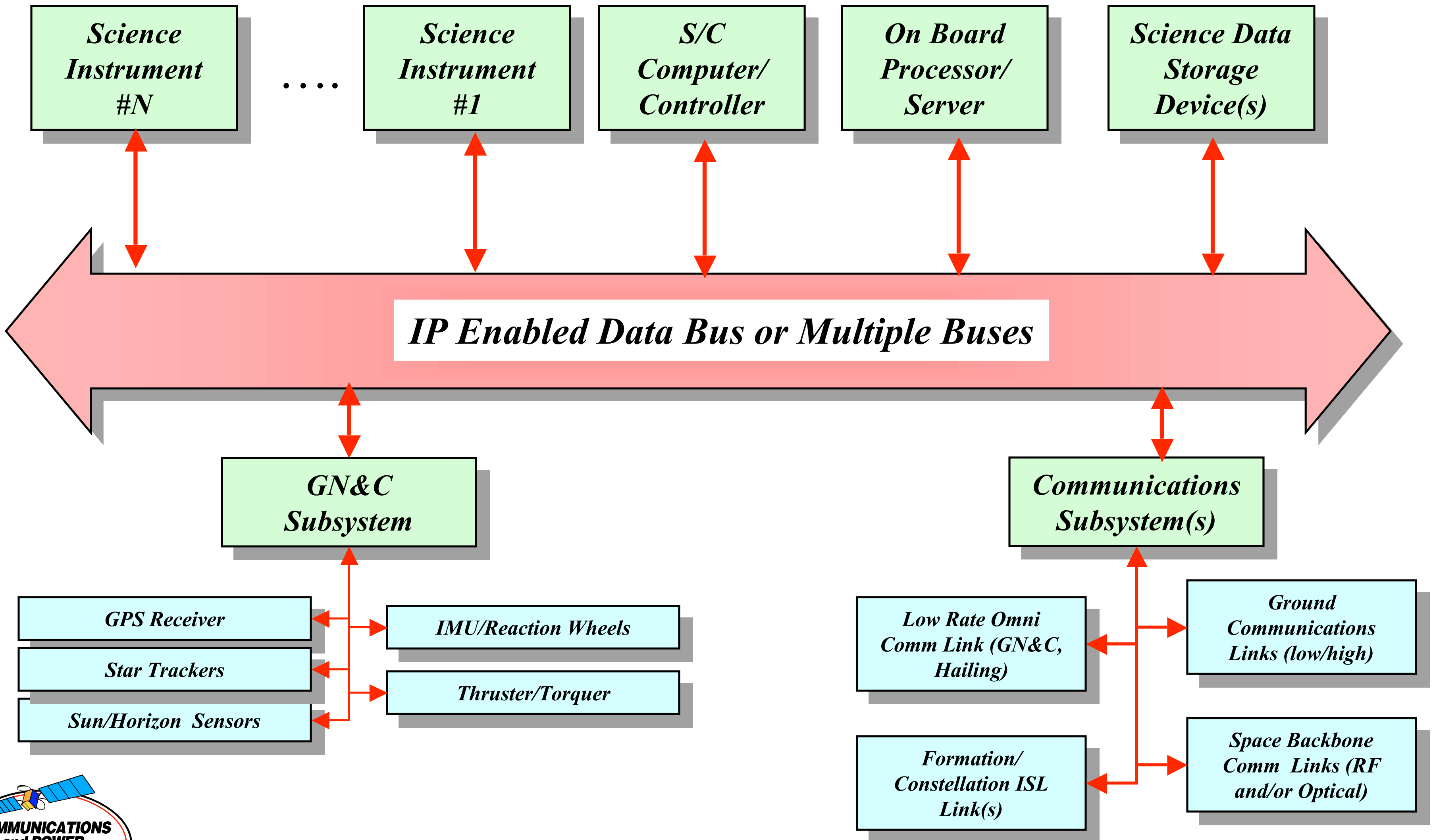
Information System (IS) Overview

- *Information System (IS): End to End data delivery (sensor to user)*
- *Assumptions:*
  - –*IP everywhere (sensors-> end user)*
  - –*Autonomous operations, scheduling, data delivery*
  - –*Interface to terrestrial internet*
- *Functional description (performance/capabilities mission dependent)*
- *Generic IS: not specific to Leonardo “2015”*
- *Utilize previously described technologies*

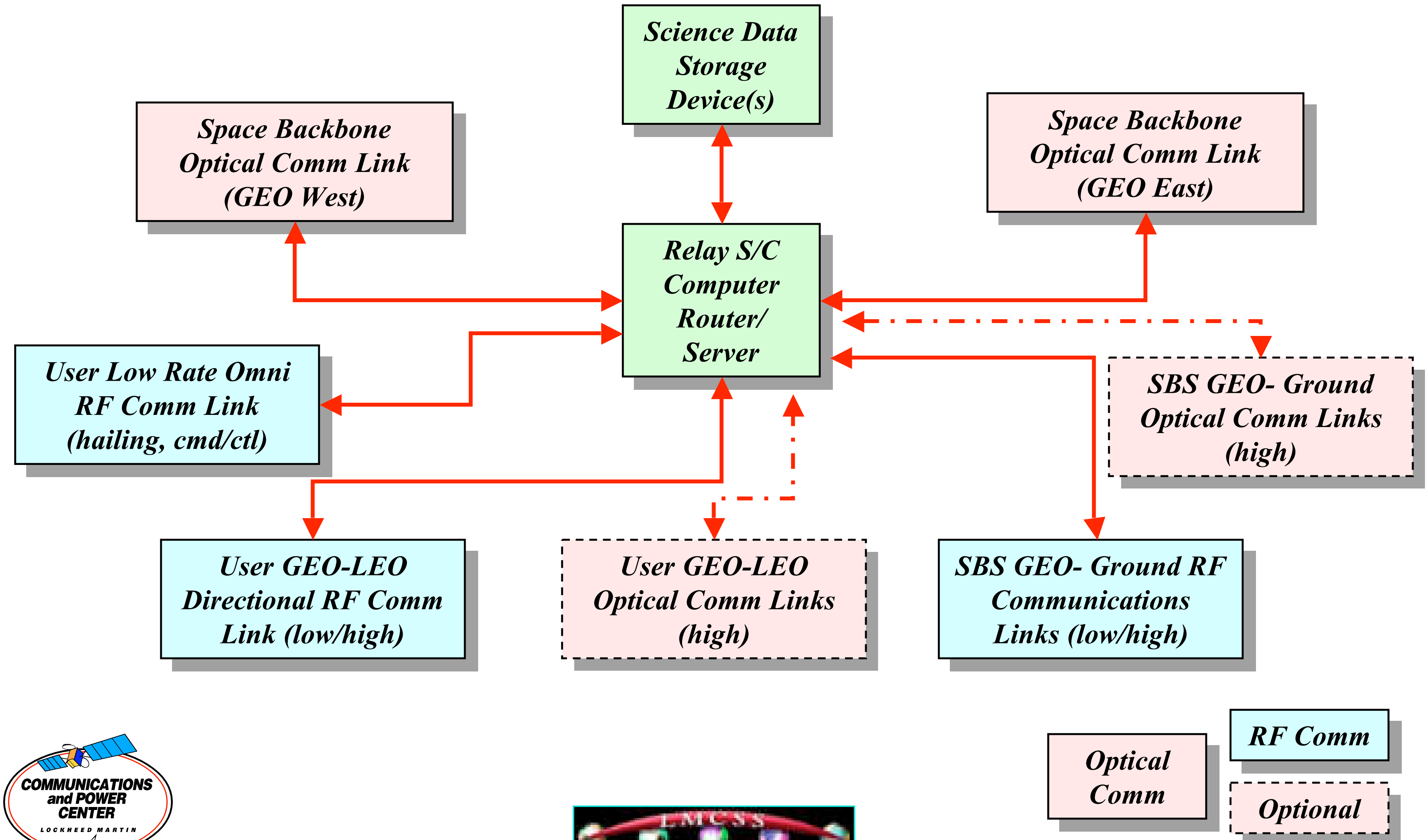
End to End IS Core Data Delivery



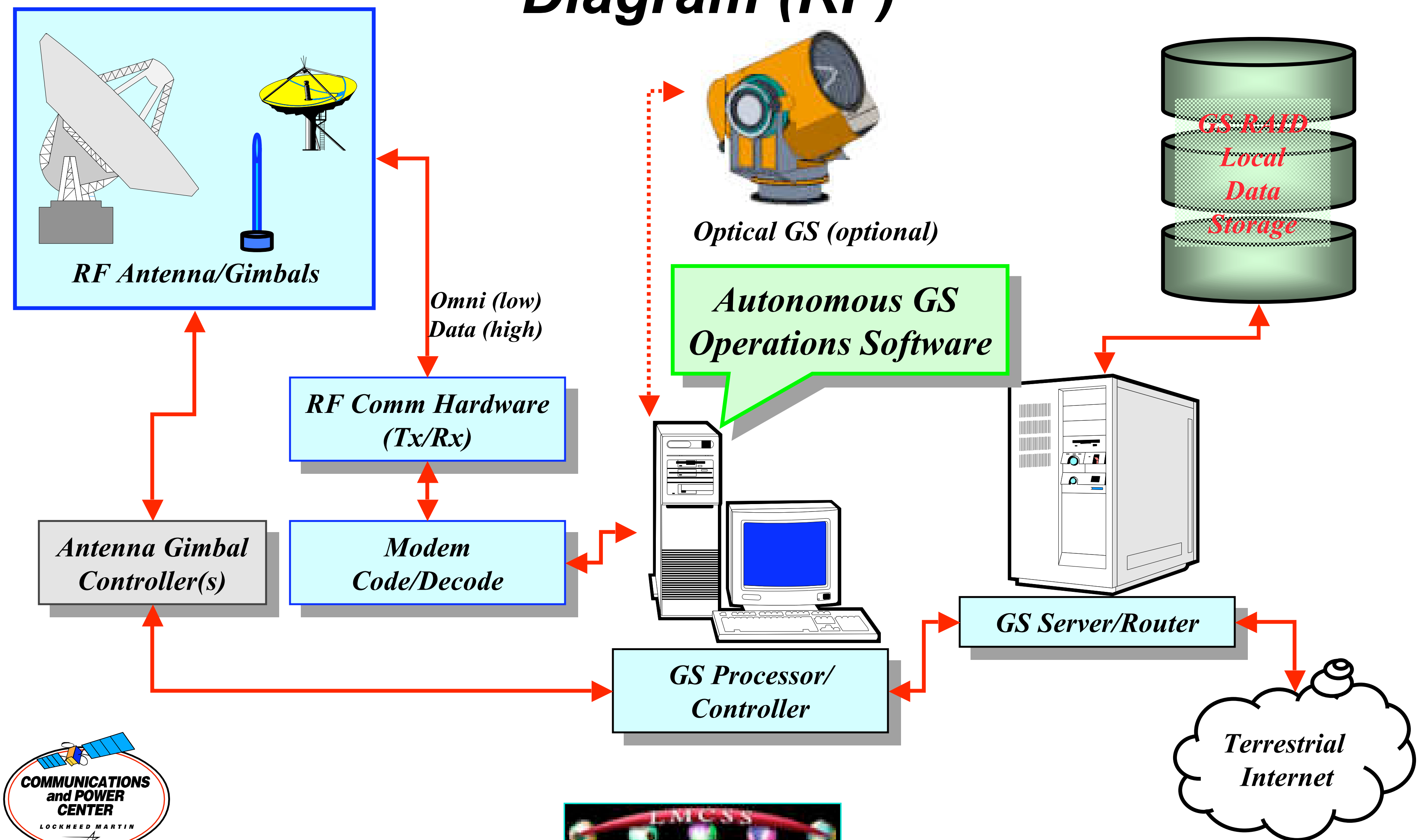
Sensor S/C IS Core Functional Block Diagram



Space Based Server (SBS) Relay S/C IS Core Functional Block Diagram



Ground Station IS Core Functional Block Diagram (RF)



Section 6: Integrated Technology Development Trades/Roadmaps

Team

Presentation Outline

TRL Process

- *Benefits*
- *Subjective*
- *Universal*
- *Areas for Improvement*

TRL Method Incorporated in NASA Management Inst. (MNI7100)

Recently Accepted by DDRE for Assessment of Emerging Technologies for Aerospace Applications

TRL Process Considerations

- *Implementation of flowdown: mission--requirements--functions*
- *Functions distilled into technologies*
- *Technologies segmented to components (systems-subsystems--components)*
- *Ranking of Technologies dependent on broad based accepted algorithm*
- *Algorithm contains: need date, current TRL, TRL improvement rate,complexity factor, auxiliary factors)*
- *Auxiliary factors contain: interdependence on other technologies, synergism of progression to mission value, others*
- *Eye of the beholder normalization need*

Technology Readiness Levels

TRL 1	Basic principles observed and reported	Feasibility
TRL 2	Technology concept and/or application formulated	
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	
TRL 4	Component and/or breadboard validation in laboratory environment	Demonstrations
TRL 5	Component and/or breadboard validation in relevant environment	
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	
TRL 7	System prototype demonstration in a space environment	System Test/Flight
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	
TRL 9	Actual system "flight proven" through successful mission operations	

Assessment of Using Technology Readiness Level (TRL)

- *Technology Maturity Assessed Using Nine Stages of Development.*
- *TRL Process Heavily Biased Toward "Functional" Descriptions Without Directly Addressing Performance, e.g.*
  - *A Functional Capability Can Have a TRL 9 Rating, but Is Not Suitable for a Specific Mission Due to Cost, Mass, Power Consumption, Availability, Performance or Other Characteristics.*
- *TRLs Do Not Indicate If an Area Is Progressing Forward (Rate of Improvement) nor Actual Investment Requirements.*
- *TRLs Do Not Indicate Specific Mission Benefits.*
- *TRLs Need to Be Used in Combination With Other Parameters in a Weighted Figure-of-merit (FOM) for Evaluating Investment Goals.*

Relative Cost Estimate Method & Assumptions

- ***Dollars used as relative to absolute***
- ***2 years per TRL level baseline [but adjusted for other factors including complexity and external development]***
- ***Technologies brought to TRL 7***
- ***Fully Burdened Labor Rate of 250K$/person/year***
- ***Multiple teams used to reduce risk for complex technologies***
- ***Complexity factor used:***

  High – Multi-disciplinary team needed for innovative concept

  Medium – Reasonable advancement of current technology

  Low – Technology in hand but not used for this particular purpose, usually single discipline

Technology Ranking (TR)

- **Need for Algorithm**
- **Notional Example:**

Multi-Mission Factors

Development Time to TRL=7

$$TR = \left(\#R + \#E \cdot W_{enhance}\right) \cdot \left(1 + F_{newsci}\right) \cdot \frac{(7 - TRL) \cdot {}^{Years}/_{TRL}}{\left(T_{earliest} - T_{current}\right)}$$

Time to Earliest Insertion

Weighting Factor for Enhancement

 # Technology Required

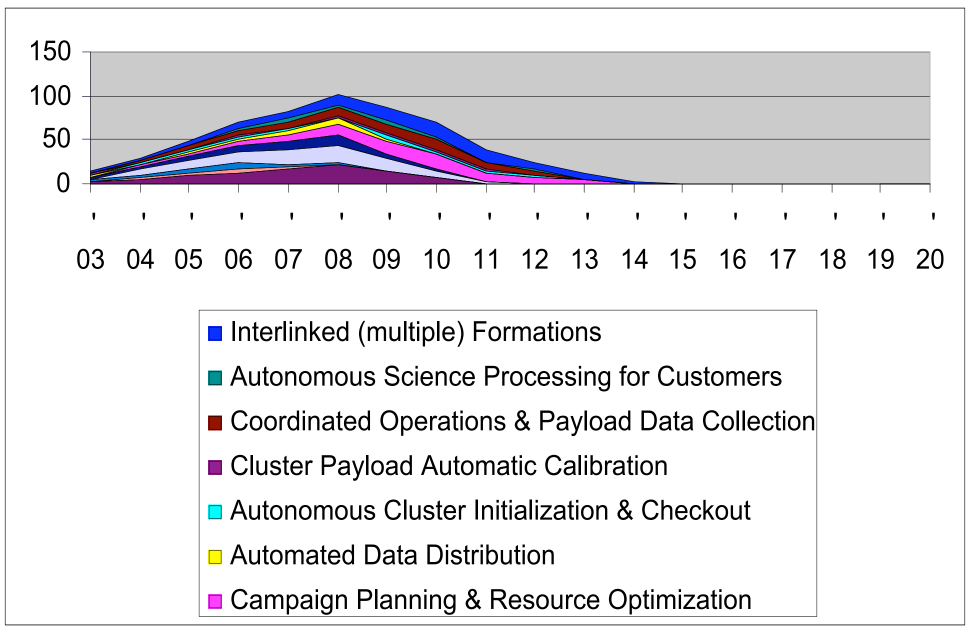
 # Technology Enhances Performance

Enable New Science Measurements

Application of Ranking Needs Rough Consensus on Factors/Values

Guidance and Operations Technology Development

Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)	Technology Item	TRL	TechArea	HW/SW	Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
			Missions: ESE				Missions: SSE								Missions: other						Development Factors									
13	12	0	x	R	R	R	R	R	R	R	R	R	R	R		R	Multi-spacecraft, Manual Deployment	9	Guidance	B										
13	12	0	x	R	R	R	R	R	R	R	R	R	R	R		R	Manual Cluster Initialization & Checkout	9	Guidance	B										
13	12	0	x	R	R	R	R	R	R	R	R	R	R	R		R	Single Payload Automatic Calibration	9	Guidance	B										
12	11	0	x	R	R	R	R	R	R	R	R	R	R	R			Resource Scheduling in Single Spacecraft	7	Guidance	S/W										
11	6	4	x	E	R	R	E	R	E	E		R	R	R			Resource Scheduling among Cluster Spacecraft	4	Guidance	S/W	H	4	20	80	40		6	9	360	$90
7	4	2	x	E			E	R		R			R	R			Coordinated Attitude Control	4	Guidance	B	L	2	10	20	10		6	6	60	$15
8	6	1	x	E	R	R		R		R			R	R			Coordinated Pointing Control	4	Guidance	B	L	2	10	20	10		6	6	60	$15
12	7	4	x	E	E	R	E	R	E	R		R	R	R		R	Autonomous Formation Operations	3	Guidance	S/W	H	4	20	80	40		8	9	360	$90
11	4	6	x	E	E	R	E	R		R	E	E	E	R			Autonomous Payload Operations for Cluster	3	Guidance	S/W	M	4	12	48	24		8	8	192	$48
5	3	1	x	E						R			R	R			Campaign Planning & Resource Optimization	3	Guidance	S/W	H	3	20	60	30	X	8	11	330	$83
11	0	10	x	E	E	E	E	E	E	E	E		E	E			Automated Data Distribution	3	Guidance	S/W	M	3	8	24	12	X	8	8	96	$24
7	0	6	x			E	E	E		E			E	E			Autonomous Cluster Initialization & Checkout	2	Guidance	B	M	2	8	16	8		10	10	80	$20
10	5	3	x		E	R	E	R		R	(E)	E	R	R			Cluster Payload Automatic Calibration	2	Guidance	B	L	1	10	10	5		10	10	50	$13
13	8	4	x	E	E	R	R	R	E	R	R	R	R	R		E	Coordinated Operations & Payload Data Collection	2	Guidance	S/W	M	3	16	48	24	X	10	11	264	$66
11	0	10	x	E		E	E	E	E	E	E	E	E	E			Autonomous Science Processing for Customers	2	Guidance	S/W	M	2	8	16	8	X	10	10	80	$20
1	0	0	x														Interlinked (multiple) Formations	2	Guidance	S/W	H	4	16	64	32		10	12	384	$96



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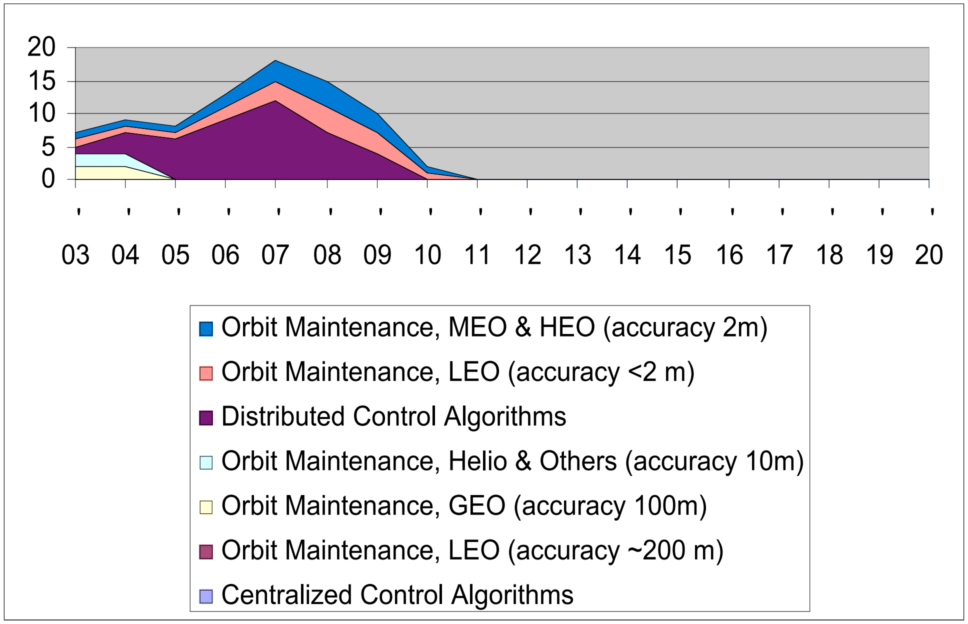
Guidance and Operations Technology Assessment

- ***Basic enabling technologies selected for immediate development***
- ***Technologies to take advantage of SensorWeb (eg.11,12) follow later***

	Technology	TRL	$M/team
1	Coordinated Attitude Control	4	$8
2	Coordinated Pointing Control	4	$8
3	Autonomous Formation Operations	3	$23
4	Autonomous Payload Operations for Cluster	3	$12
5	Coordinated Operations & Payload Data Collection	2	$22
6	Cluster Payload Automatic Calibration	2	$13
7	Autonomous Cluster Initialization & Checkout	2	$10
8	Resource Scheduling among Cluster Spacecraft	4	$23
9	Campaign Planning & Resource Optimization	3	$28
10	Autonomous Science Processing for Customers	2	$10
11	Interlinked (multiple) Formations	2	$24
12	Automated Data Distribution	3	$8

Formation Control Technology Development

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors									
			ESE				SSE								other																	
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)							Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
7	5	1	x					R	E	R			R	R		R			Centralized Control Algorithms	7	Navigation	B										
7	6	0	x	R	R	R	R		R			R							Orbit Maintenance, LEO (accuracy ~200 m)	7	Navigation	B										
3	2	0	x				R				R								Orbit Maintenance, GEO (accuracy 100m)	6	Navigation	B	L	2	8	16	8		2	2	16	$4
7	6	0	x				R	R		R	R		R	R					Orbit Maintenance, Helio & Others (accuracy 10m)	6	Navigation	B	L	2	8	16	8		2	2	16	$4
7	4	2	x		E	R	R						R	R		E			Distributed Control Algorithms	4	Navigation	B	M	4	12	48	24		6	7	168	$42
5	0	4	x	E	E		E									E			Orbit Maintenance, LEO (accuracy <2 m)	3	Navigation	B	M	2	8	16	8		8	8	64	$16
4	3	0	x				R				R	R							Orbit Maintenance, MEO & HEO (accuracy 2m)	3	Navigation	B	L	2	8	16	8		8	8	64	$16



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Formation Control Technology Assessment

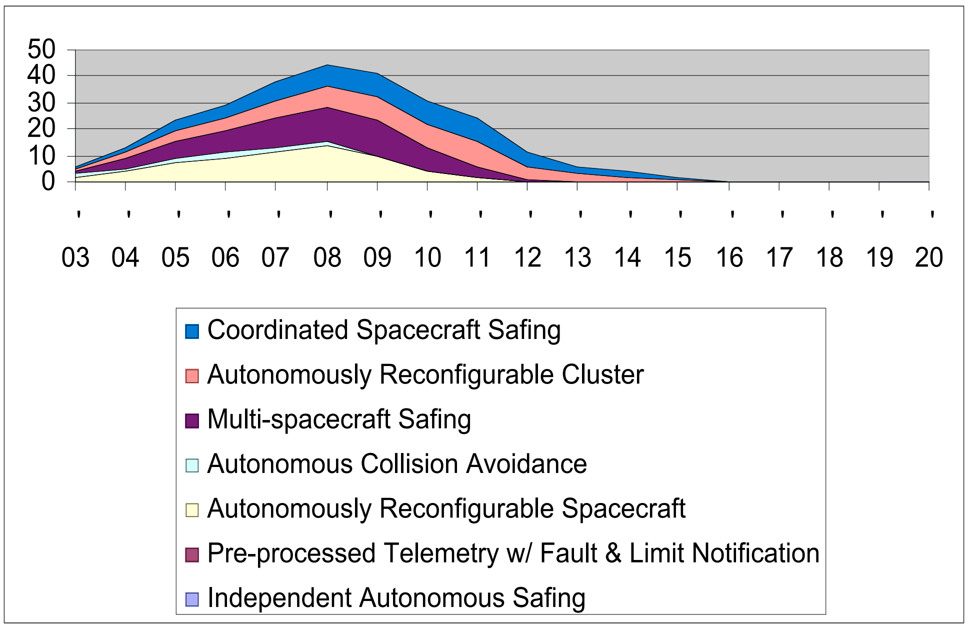
- ***This area is well into development***

	Technology	TRL	$M/team
1	Distributed Control Algorithms	4	$11
2	Orbit Maintenance, LEO (accuracy <2 m)	3	$8
3	Orbit Maintenance, MEO & HEO (accuracy 2m)	3	$8
4	Orbit Maintenance, Helio & Others (accuracy 10m)	6	$2
5	Orbit Maintenance, GEO (accuracy 100m)	6	$2

FDIR Technology Development

Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004) (Missions: ESE)	Leonardo BRDF Baseline (2008) (Missions: ESE)	Leonardo BRDF Beyond (2015) (Missions: ESE)	MMS (2008) (Missions: SSE)	LISA (2008) (Missions: SSE)	GEC (2009) (Missions: SSE)	TPF (2011) (Missions: SSE)	Magneto-Constellation (2011) (Missions: SSE)	Radiation Belt Mapper (2015) (Missions: SSE)	Constellation-X (2015) (Missions: SSE)	SISP (2015) (Missions: SSE)	GPS III (2005) (Missions: other)	Orbital Express (2005) (Missions: other)			Technology Item
13	12	0	x	R	R	R	R	R	R	R	R	R	R	R		R			Independent Autonomous Safing
13	1	11	x	E	E	E	E	E	E	E	E	R	E	E		E			Pre-processed Telemetry w/ Fault & Limit Notification
7	0	6	x			E	E	E		E			E	E					Autonomously Reconfigurable Spacecraft
9	4	4	x	E		E	E	E		R			R	R		R			Autonomous Collision Avoidance
8	1	6	x			E	E	E		E			E	R		E			Multi-spacecraft Safing
6	1	4	x			E	E			E			E	R					Autonomously Reconfigurable Cluster
7	1	5	x			E	E	E		E			E	R					Coordinated Spacecraft Safing

Technology Item	TRL	TechArea	HW/SW	Complexity (Development Factors)	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
Independent Autonomous Safing	9	FDIR	B										
Pre-processed Telemetry w/ Fault & Limit Notification	9	FDIR	B										
Autonomously Reconfigurable Spacecraft	4	FDIR	B	H	4	14	56	28		6	9	252	$63
Autonomous Collision Avoidance	4	FDIR	B	L	2	6	12	6		6	6	36	$9
Multi-spacecraft Safing	2	FDIR	S/W	M	4	14	56	28		10	10	280	$70
Autonomously Reconfigurable Cluster	2	FDIR	S/W	M	4	10	40	20		10	13	260	$65
Coordinated Spacecraft Safing	2	FDIR	S/W	H	4	10	40	20		10	13	260	$65



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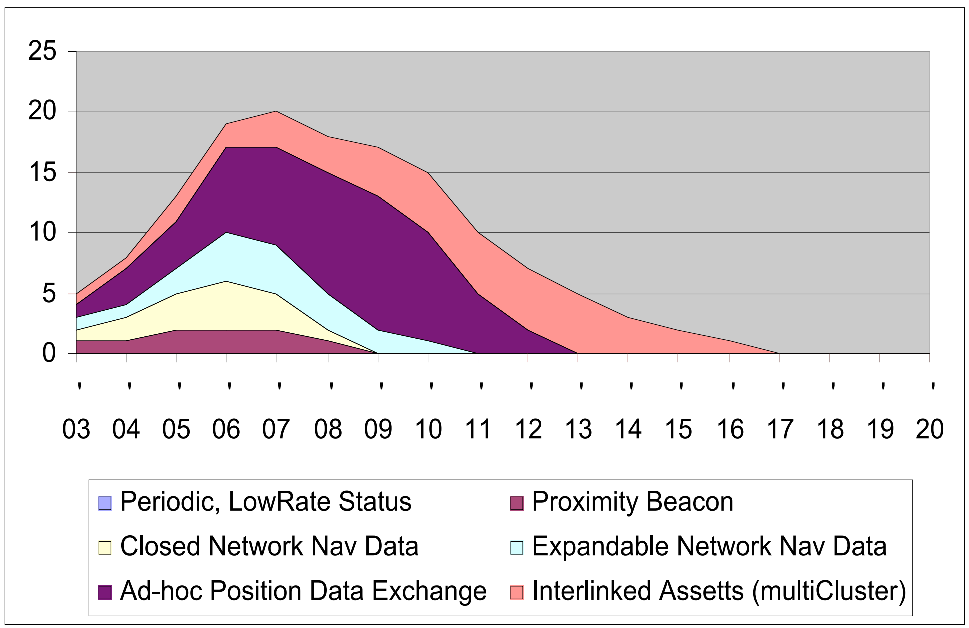
FDIR Technology Assessment

- ***Extremely important for effective use of formations to ensure safety and to ensure continuing data acquisition***

	Technology	TRL	$M/team
1	Multi-spacecraft Safing	2	$18
2	Autonomously Reconfigurable Spacecraft	4	$16
3	Autonomously Reconfigurable Cluster	2	$16
4	Coordinated Spacecraft Safing	2	$16
5	Autonomous Collision Avoidance	4	$5

Upper Level NavComm Technology Development

			Missions: ESE				Missions: SSE								Missions: other				Technology Item	TRL	TechArea	HW/SW	Development Factors									
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)							Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
13	7	5	x	R	R	R	R	E	E	E	E	R	R	R		E			Periodic, LowRate Status	9	NavCom&Ops	B										
10	2	7	x	E		E	E	E	E	E	E		R	R					Proximity Beacon	4	NavCom&Ops	B	L	2	6	12	6		6	6	36	$9
10	6	3	x	E		R	R	R		R	E		R	R		E			Closed Network Nav Data	4	NavCom&Ops	B	L	3	6	18	9		6	6	54	$14
3	0	2	x								E			E					Expandable Network Nav Data	4	NavCom&Ops	S/W	L	3	6	18	9		6	8	72	$18
2	0	1	x													E			Ad-hoc Position Data Exchange	3	NavCom&Ops	B	M	4	12	48	24		8	10	240	$60
2	0	1	x								E								Interlinked Assetts (multiCluster)	2	NavCom&Ops	B	H	3	8	24	12		10	14	168	$42



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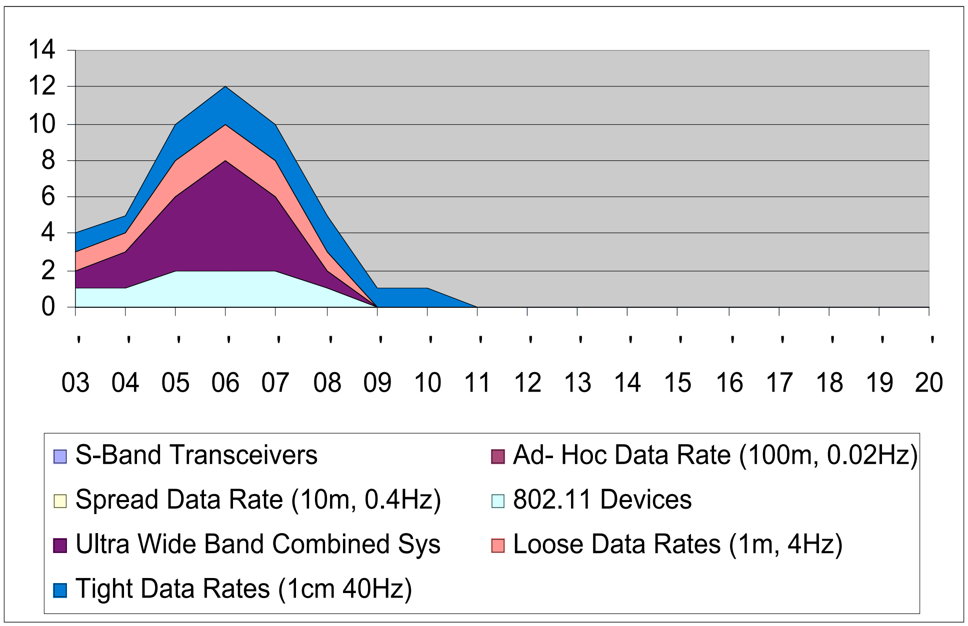
Upper Level NavComm Technology Assessment

- ***Adding Expandable Network for Navigation Data Exchange is a very important enabler for expanded SensorWeb operations***

	Technology	TRL	$M/team
1	Closed Network Nav Data	4	$5
2	Proximity Beacon	4	$5
3	Expandable Network Nav Data	4	$6
4	Ad-hoc Position Data Exchange	3	$15
5	Interlinked Assetts (multiCluster)	2	$14

NavComm Transceiver Technology Development

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors									
			ESE				SSE								other																	
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)							Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
13	11	0	x	R	R	R	R	R	R	R	(R)	R	R	R		R			S-Band Transceivers	9	NavTransceiver	H/W										
2	1	0	x													R			Ad- Hoc Data Rate (100m, 0.02Hz)	7	NavTransceiver	H/W										
2	0	1	x			E													Spread Data Rate (10m, 0.4Hz)	7	NavTransceiver	H/W										
4	0	3	x							E			E	E					802.11 Devices	4	NavTransceiver	H/W	L	2	6	12	6	X	6	6	36	$9
4	0	3	x							E			E	E					Ultra Wide Band Combined Sys	4	NavTransceiver	H/W	M	2	12	24	12	X	6	6	72	$18
4	0	0	x				x						x	x					Loose Data Rates (1m, 4Hz)	4	NavTransceiver	H/W	L	2	6	12	6		6	6	36	$9
3	0	2	x					E		E									Tight Data Rates (1cm 40Hz)	3	NavTransceiver	H/W	L	2	6	12	6		8	8	48	$12



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NavComm Transceiver Technology Assessment

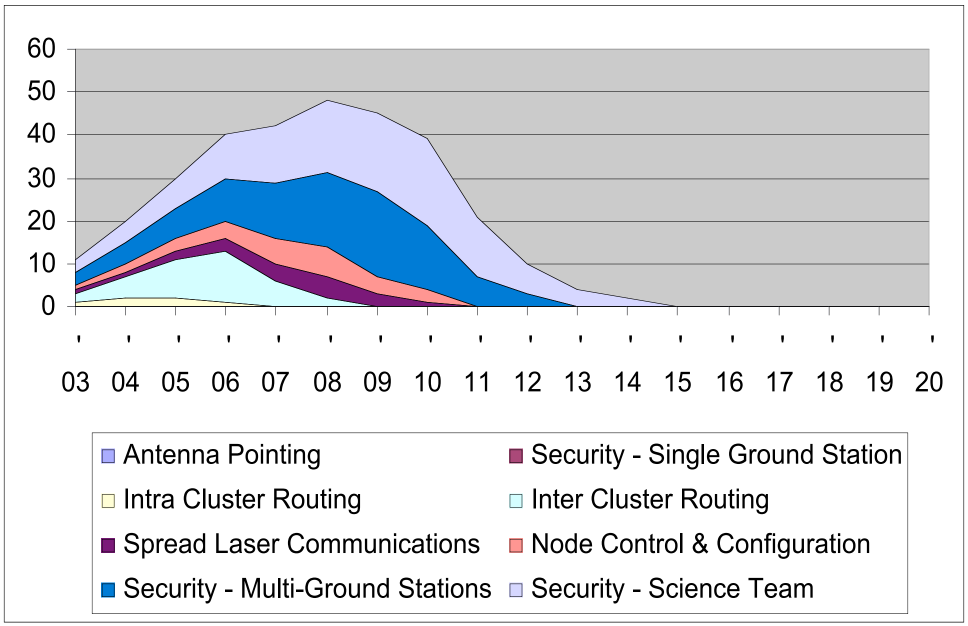
- ***Communication of navigation data is not a stressing area. Selection of appropriate technology is mission driven.***
- ***Combined Comm/Nav system could deliver improved accuracy at reduced cost***

	Technology	TRL	$M/team
1	Ultra Wide Band Combined Sys	4	$9
2	802.11 Devices	4	$5
3	Tight Data Rates (1m, 4Hz)	4	$5
4	Complex Data Rates (1cm 40Hz)	3	$6

Science Communications Technology Development

Technology Item	Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Missions: ESE: Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	SSE: MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	other: GPS III (2005)	Orbital Express (2005)		
Antenna Pointing	11	8	2	x	R	R	R	R	R		R	E		R	R		E		
Security - Single Ground Station	13	12	0	x	R	R	R	R	R	R	R	R	R	R	R		R		
Intra Cluster Routing	10	3	6	x	E		R	E	E		R	E		E	R		E		
Inter Cluster Routing	6	0	5	x	E		E	E				E			E				
Spread Laser Communications	8	0	7	x			E	E	E		E	E		E	E				
Node Control & Configuration	8	1	6	x			E	E	E		E	R		E	E				
Security - Multi-Ground Stations	11	10	0	x	R		R	R	R	R	R	R	R	R	R				
Security - Science Team	10	9	0	x	R		R		R	R	R	R	R	R	R				

Technology Item	TRL	TechArea	HW/SW	Development Factors: Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
Antenna Pointing	9	SciComm	B										
Security - Single Ground Station	9	SciComm	S/W										
Intra Cluster Routing	6	SciComm	B	L	2	6	12	6		2	4	24	$6
Inter Cluster Routing	6	SciComm	B	H	3	16	48	24		2	6	144	$36
Spread Laser Communications	4	SciComm	B	M	2	10	20	10		6	8	80	$20
Node Control & Configuration	3	SciComm	S/W	L	3	10	30	15	X	8	8	120	$30
Security - Multi-Ground Stations	3	SciComm	S/W	H	4	20	80	40	X	8	10	400	$100
Security - Science Team	2	SciComm	S/W	H	4	20	80	40	X	10	12	480	$120



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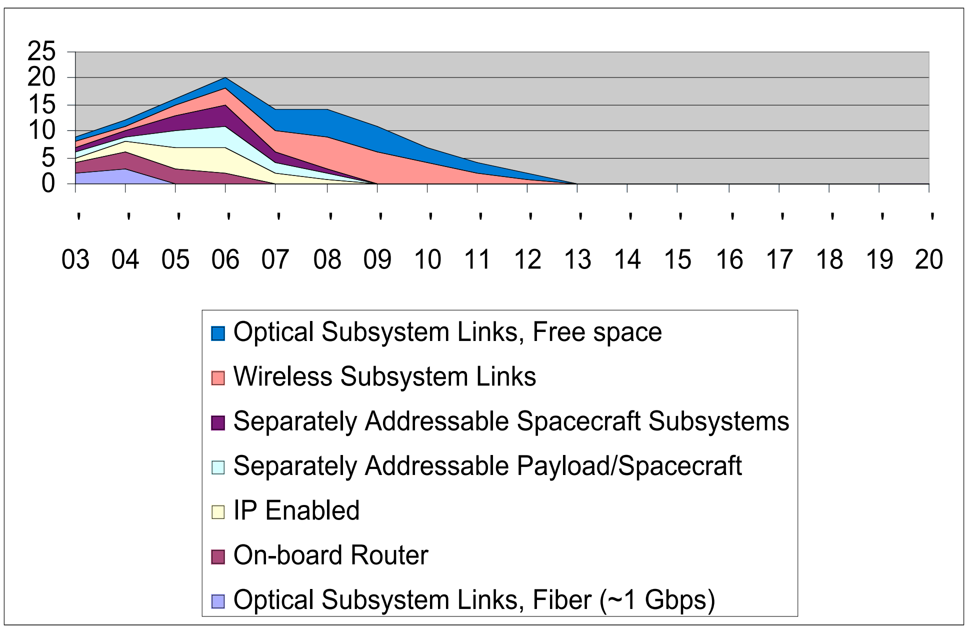
Science Communications Technology Assessment

- ***Ability to reconfigure formations and allocate sensing resources engenders major increase in science productivity***
- ***SensorWeb enables access by multiple teams but increased access control is required***

	Technology	TRL	$M/team
1	Intra Cluster Routing	6	$3
2	Security - Multi-Ground Stations	3	$25
3	Node Control & Configuration	3	$10
4	Security - Science Team	2	$30
5	Spread Laser Communications	4	$10
6	Inter Cluster Routing	6	$12

Spacecraft Data Bus Technology Development

Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Missions: ESE: Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	SSE: MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	other: GPS III (2005)	Orbital Express (2005)			Technology Item	TRL	TechArea	HW/SW	Development Factors: Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
3	0	2	x	E		E													Optical Subsystem Links, Fiber (~1 Gbps)	6	DataBus	H/W	M	2	10	20	10	X	2	2	20	$5
8	0	7	x			E	E	E		E			E	E		E			On-board Router	5	DataBus	H/W	M	2	10	20	10		4	4	40	$10
12	0	10	x	E	E	E	E	E	E	E	(E)		E	E		E			IP Enabled	4	DataBus	B	M	2	10	20	10		6	6	60	$15
11	0	9	x	E	E	E	E	E	E	E	(E)		E	E					Separately Addressable Payload/Spacecraft	4	DataBus	B	L	2	8	16	8		6	6	48	$12
2	0	1	x	E															Separately Addressable Spacecraft Subsystems	4	DataBus	B	L	2	8	16	8		6	6	48	$12
1	0	0	x																Wireless Subsystem Links	3	DataBus	H/W	M	2	12	24	12	X	8	10	120	$30
1	0	0	x																Optical Subsystem Links, Free space	3	DataBus	H/W	M	2	10	20	10	X	8	10	100	$25



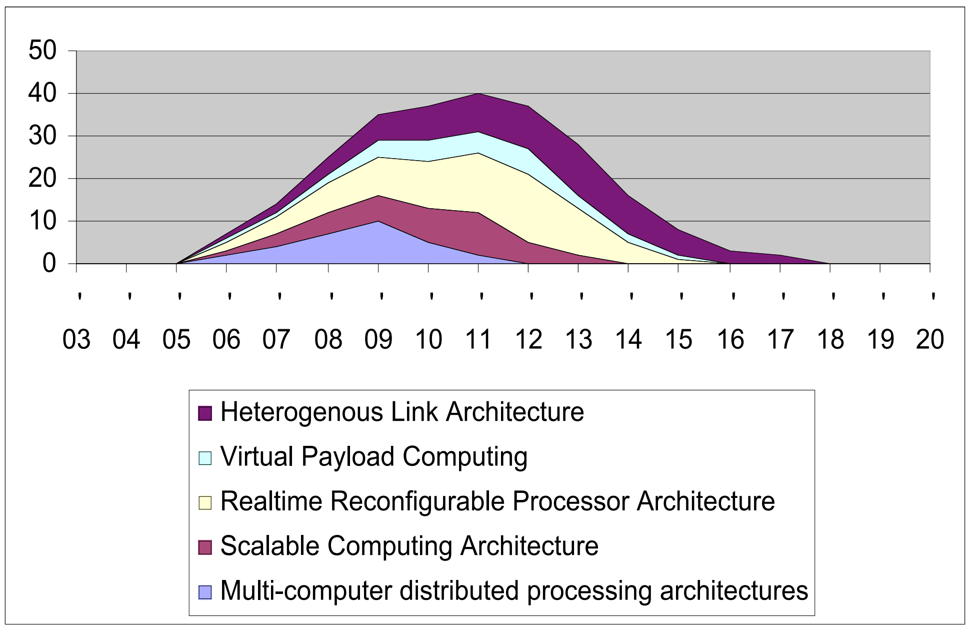
Spacecraft Data Bus Technology Assessment

- ***Individual spacecraft designs must be updated to enable access to SensorWeb***

	Technology	TRL	$M/team
1	IP Enabled	4	$8
2	Separately Addressable Payload/Spacecraft	4	$6
3	On-board Router	5	$5
4	Separately Addressable Spacecraft Subsystems	4	$6
5	Optical Subsystem Links, Fiber (~1 Gbps)	6	$3
6	Wireless Subsystem Links	3	$15
7	Optical Subsystem Links, Free space	3	$13

Space Computing Technology Development

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors									
			ESE				SSE								other																	
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)							Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars
8	1	6	x	E	E	R		E		E			E	E					Multi-computer distributed processing architectures	6	DistComp	B	L	4	10	40	20	X	2	6	120	$30
5	0	4	x	E	E	E								E					Scalable Computing Architecture	4	DistComp	B	L	4	10	40	20	X	6	8	160	$40
4	0	3	x	E	E	E													Realtime Reconfigurable Processor Architecture	4	DistComp	B	M	4	16	64	32	X	6	10	320	$80
4	0	3	x	E	E	E													Virtual Payload Computing	2	DistComp	B	L	3	8	24	12	X	10	10	120	$30
1	0	0	x																Heterogenous Link Architecture	2	DistComp	B	L	4	12	48	24	X	10	12	288	$72



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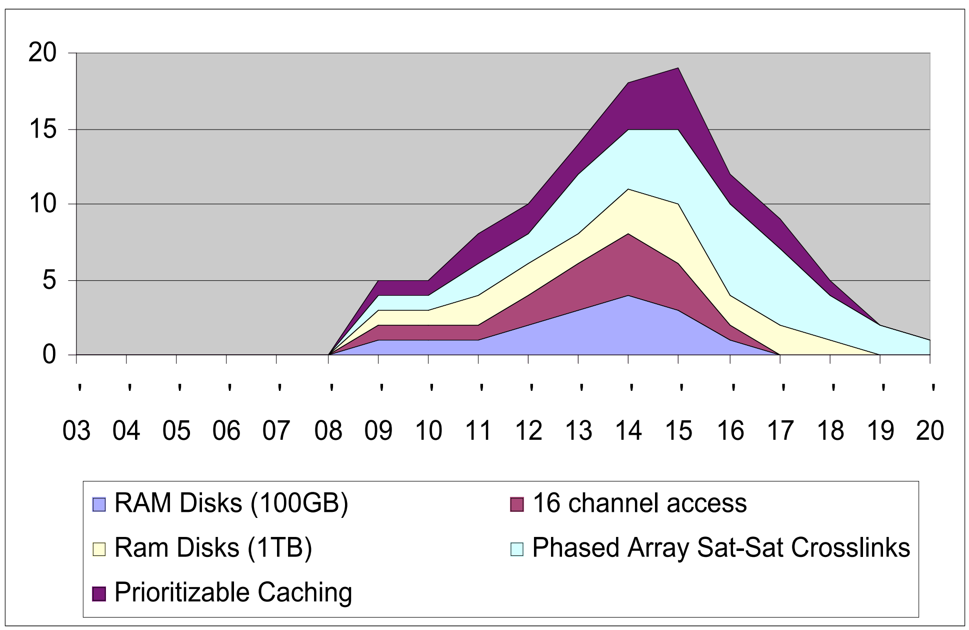
Space Computing Technology Assessment

- ***Joint use of computing resources and reconfiguration of local and virtual science nets is a downstream technology need but enabling for space-based servers. Long development time, especially for flight qualification, indicates an early start is desirable.***

	Technology	TRL	$M/team
1	Multi-computer distributed processing architectures	6	$8
2	Scalable Computing Architecture	4	$10
3	Realtime Reconfigurable Processor Architecture	4	$20
4	Virtual Payload Computing	2	$10
5	Heterogenous Link Architecture	2	$18

Space Data Server Technology Development

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors									
			ESE				SSE								other																	
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web	EOS A Train [Aqua, Aura, ...] (2004)	Leonardo BRDF Baseline (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2009)	TPF (2011)	Magneto-Constellation (2011)	Radiation Belt Mapper (2015)	Constellation-X (2015)	SISP (2015)	GPS III (2005)	Orbital Express (2005)							Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years	Total Dollars ($M)
2	0	1	x	E															RAM Disks (100GB)	3	Servers	H/W	M	2	8	16	8	X	8	8	64	$16
2	0	1	x	E															16 channel access	3	Servers	H/W	M	2	8	16	8		8	8	64	$16
2	0	1	x	E															Ram Disks (1TB)	2	Servers	H/W	M	2	8	16	8	X	10	10	80	$20
2	0	1	x	E															Phased Array Sat-Sat Crosslinks	2	Servers	H/W	M	2	12	24	12	X	10	12	144	$36
1	0	0	x																Prioritizable Caching	2	Servers	S/W	M	2	8	16	8		10	10	80	$20



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Space Data Server Technology Assessment

- ***These are all downstream technologies and active work is occurring externally. No immediate development is suggested.***

	Technology	TRL	$M/team
1	RAM Disks (100GB)	3	$8
2	16 channel access	3	$8
3	Ram Disks (1TB)	2	$10
4	Prioritizable Caching	2	$10
5	Phased Array Sat-Sat Crosslinks	2	$18

Key Formation Technologies for Leonardo 2015 Mission

Component Technologies Level

- Ultra Wide Band Combined Sys
- Node Control & Configuration
- IP Enabled
- Separately Addressable Payload/Spacecraft
- On-board Router
- Multi-computer distributed processing architectures

System or Functional Level Development

- Coordinated Attitude Control
- Coordinated Pointing Control
- Autonomous Formation Operations
- Autonomous Payload Operations for Cluster
- Coordinated Operations & Payload Data Collection
- Distributed Control Algorithms
- Multi-spacecraft Safing
- Autonomously Re-configurable Spacecraft
- Autonomously Re-configurable Cluster
- Coordinated Spacecraft Safing
- Closed Network Nav Data
- Expandable Network Nav Data
- Intra Cluster Routing
- Security - Multi-Ground Stations
- Security - Science Team
- Real-time Re-configurable Network Computing

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Key Formation Technologies

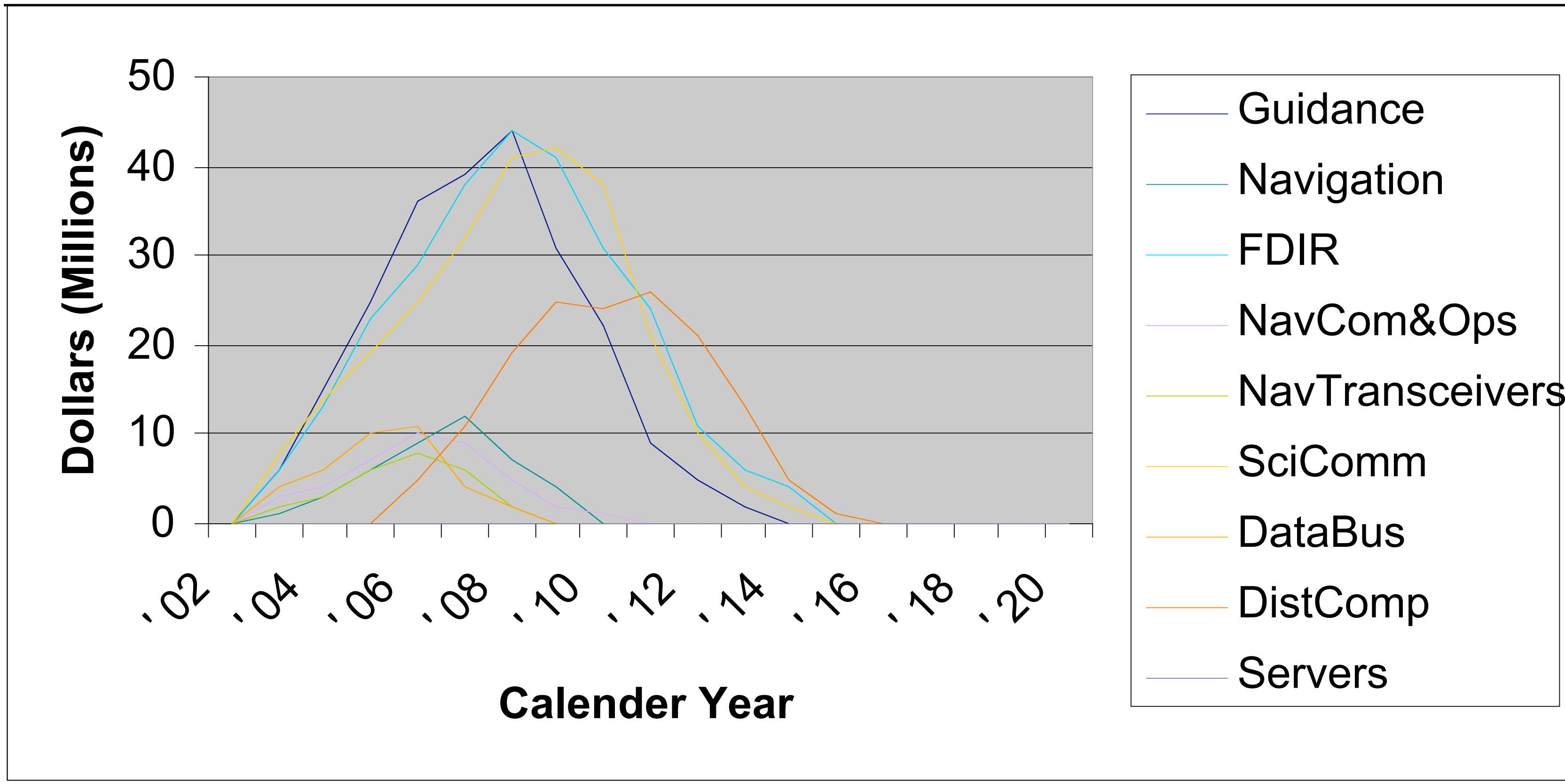
Component Technologies Level

- Autonomous Collision Avoidance
- Proximity Beacon
- Ultra Wide Band Combined Sys
- 802.11 Devices
- Node Control & Configuration
- IP Enabled
- Separately Addressable Payload/Spacecraft
- On-board Router
- Multi-computer distributed processing architectures

System or Functional Level Development

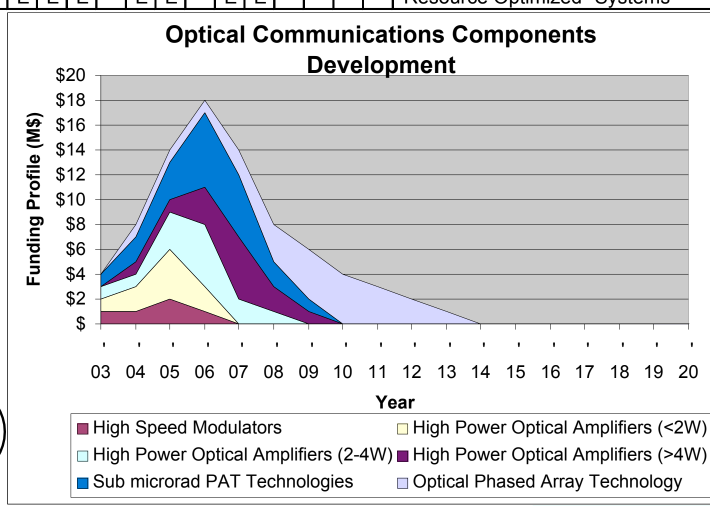
- Coordinated Attitude Control
- Coordinated Pointing Control
- Autonomous Formation Operations
- Autonomous Payload Operations for Cluster
- Coordinated Operations & Payload Data Collection
- Distributed Control Algorithms
- Multi-spacecraft Safing
- Autonomously Re-configurable Spacecraft
- Autonomously Re-configurable Cluster
- Coordinated Spacecraft Safing
- Closed Network Nav Data
- Expandable Network Nav Data
- Intra Cluster Routing
- Security - Multi-Ground Stations
- Security - Science Team
- Scalable Computing Architecture
- Real-time Re-configurable Network Computing

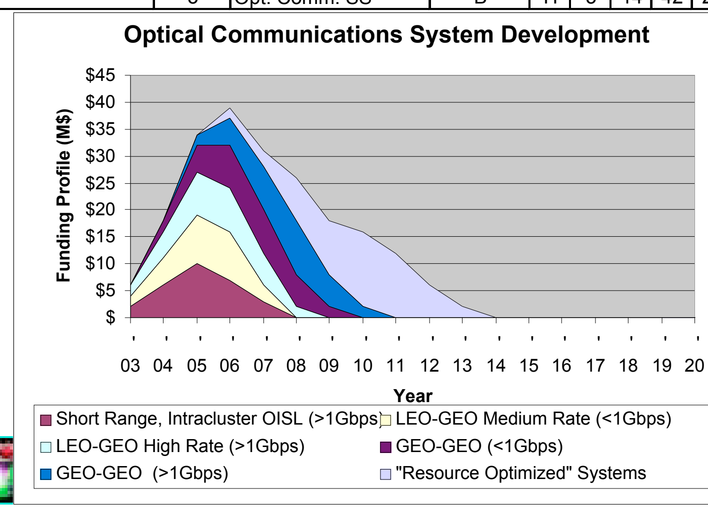
Key FF Technology Development Profiles



Optical Communications Technology

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors								
			ESE				ESE								Other																
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web		Leonardo BRDF (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2008)	TPF (2012)	Magneto-Constellation (2010)	Radiation Belt Mapper (2009)	Constellation-X	SISP	GPS III (2005)	Orbital Express			**Optical Communications Technology Development**				Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years
8	0	8	E			E	E	E		E	E		E	E					Diode Laser Technology	7	Opt. Comp. Dev.	H									
8	0	8	E			E	E	E		E	E		E	E					High Speed Modulators	5	Opt. Comp. Dev.	H	L	2	4	8	4	X	4	4	16
8	0	8	E			E	E	E		E	E		E	E					High Power Optical Amplifiers (<2W)	5	Opt. Comp. Dev.	H	M	2	8	16	8	X	4	4	32
8	0	8	E			E	E	E		E	E		E	E					High Power Optical Amplifiers (2-4W)	4	Opt. Comp. Dev.	H	M	2	8	16	8	X	6	6	48
3	0	3	E										E	E					High Power Optical Amplifiers (>4W)	3	Opt. Comp. Dev.	H	M	2	8	16	8	X	6	6	48
8	0	8	E			E	E	E		E	E		E	E					Fast Steering Mirror Technology (FSM)-PAT	8	Opt. Comp. Dev.	H									
3	0	3	E										E	E					Sub microrad PAT Technologies	4	Opt. Comp. Dev.	B	H	3	8	24	12	X	6	6	72
8	0	8	E			E	E	E		E	E		E	E					Optical Phased Array Technology	3	Opt. Comp. Dev.	B	H	3	5	15	7.5	X	8	10	75
0	0	0																													
6	0	6	E			E	E	E		E	E								Short Range, Intracluster OISL (Low Data Rate)	7	Opt. Comm. SS	B									
6	0	6	E			E	E	E		E	E								Short Range, Intracluster OISL (>1Gbps)	5	Opt. Comm. SS	B	M	2	14	28	14	X	4	5	70
7	0	7				E	E	E		E	E		E	E					LEO-GEO Low Rate (<50Mbps)	7	Opt. Comm. SS	B									
8	0	8	E			E	E	E		E	E		E	E					LEO-GEO Medium Rate (<1Gbps)	5	Opt. Comm. SS	B	M	2	14	28	14	X	4	5	70
8	0	8	E			E	E	E		E	E		E	E					LEO-GEO High Rate (>1Gbps)	4	Opt. Comm. SS	B	M	2	14	28	14	X	6	6	84
1	0	1	E																GEO-GEO (<1Gbps)	4	Opt. Comm. SS	B	M	2	14	28	14	X	6	6	84
1	0	1	E																GEO-GEO (>1Gbps)	4	Opt. Comm. SS	B	H	2	14	28	14	X	6	6	84
8	0	8	E			E	E	E		E	E		E	E					"Resource Optimized" Systems	3	Opt. Comm. SS	B	H	3	14	42	21	X	8	8	168





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Key Technologies for Optical Intersatellite Communications

Component Technologies Level

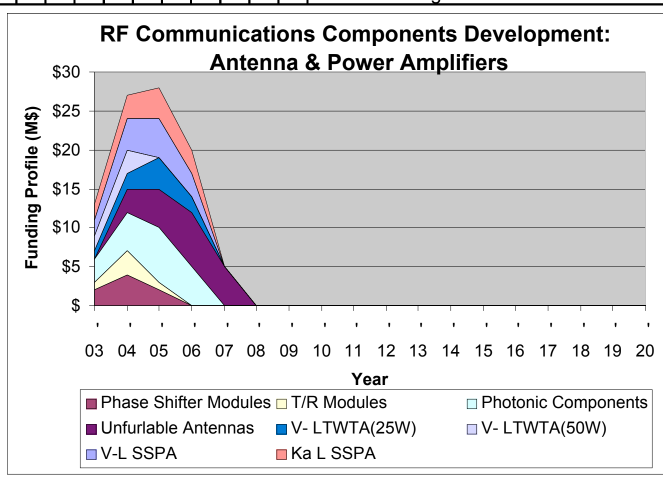
- PAT technologies
  - –high performance (sub microrad)
  - –cost/performance
- Efficient, High Power Optical Amplifiers
- Wavelength Division Multiplexing (WDM)
- Non Mechanical Beam Steering
- Lightweight Optics (holographic/ diffractive)

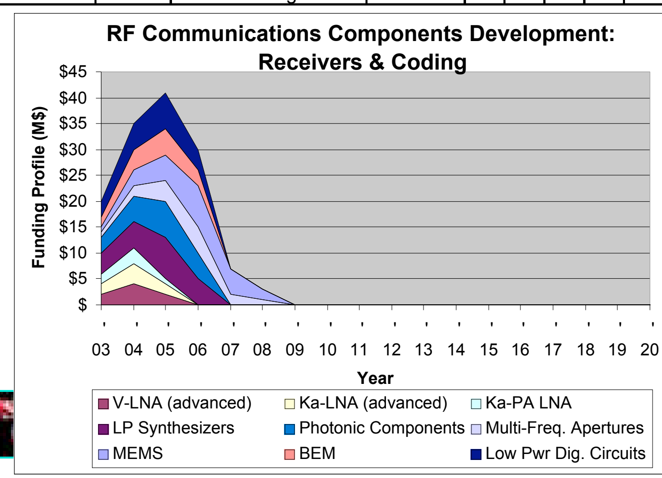
"OISL Terminal" Level Development

- System Flight Demo
- "Resource" Optimized Systems
  - –LEO-LEO (Teledesic)
  - –Very Short Range/Resource Constrained (microsat,nanosat)
  - –LEO-GEO; LEO/GEO-UAV
- Autonomous "Demand Access" OISL operations (RF hailing, signaling for access)
- Optical Communication Standard Rates

RF Communications Technology

			Missions																Technology Item	TRL	TechArea	HW/SW	Development Factors								
			ESE				ESE								Other																
Number of Users, Total	Number of Users, Required	Nmber of Users, Enhancing	Sensor Web		Leonardo BRDF (2008)	Leonardo BRDF Beyond (2015)	MMS (2008)	LISA (2008)	GEC (2008)	TPF (2012)	Magneto-Constellation (2010)	Radiation Belt Mapper (2009)	Constellation-X	SISP	GPS III (2005)	Orbital Express			***RF Communication Technology Development***				Complexity	Number Teams	Team Size (inc.test)	Engineers per Year (pk)	Engineers per Year (av)	Affected by Ext Devel	Years from (TRL)	Years (Adjusted)	Labor Years
3	0	3	E		E	E													Phase Shifter Modules	4	Antenna & Phased	H	M	2	6	12	6		3	3	18
3	0	3	E		E	E													T/R Modules	4	Antenna & Phased	H	M	2	4	8	4		3	3	12
4	0	4	E		E	E		E											Photonic Components	3	Antenna & Phased	H	H	3	7	21	11	X	4	4	42
3	0	3	E					E		E									Unfurlable Antennas	5	Antenna & Phased	H	M	3	7	21	11		4	4	42
																										0	0				0
2	0	2	E			E													60 GHz LTWTA (25W)-Coupled Cavity Design	4	Pwr Amplifiers	H	M	2	5	10	5		4	4	20
2	0	2	E			E													60 GHz ITWTA (50W)- Needs Qual.	6	Pwr Amplifiers	H	M	2	5	10	5		2	2	10
4	0	4	E		E	E									E				60 GHz Linear SSPA (High Efficiency)	3	Pwr Amplifiers	H	M	2	10	20	10		4	4	40
6	1	5	R		E	E		E		E					E				Ka Band Linear SSPA (High Efficiency)	4	Pwr Amplifiers	H	M	2	8	16	8		4	4	32
																										0	0				0
4	0	4	E		E	E									E				60GHz LNA - Low Bias, Low Noise Figure, Cryo	3	RF Receiver Tech	H	M	2	6	12	6		3	3	18
6	0	6	E		E	E		E		E					E				Ka Band LNA- Low Bias, Low Noise Figure, Cryo	4	RF Receiver Tech	H	M	2	6	12	6		3	3	18
4	0	4	E		E	E									E				Phased Array Ka Band LNA- Low Bias,NF, TEC	3	RF Receiver Tech	H	M	2	4	8	4		3	3	12
2	0	2	E												E				Low Power Synthesizers	2	RF Receiver Tech	H	H	3	8	24	12		3	4	48
2	0	2	E					E											Photonic Components	3	RF Receiver Tech	H	H	3	7	21	11		4	4	42
3	1	2	R		E	E													Multi-frequency Apertures	3	RF Receiver Tech	H	H	3	4	12	6		6	6	36
7	0	7	E		E	E		E	E	E					E				MEMS Technology (multi-component applications)	3	RF Receiver Tech	H	H	3	5	15	7.5		6	6	45
																										0	0				0
3	2	1	R		E	R													Bandwidth Efficient Modulators (3-5 Bits/sym), Low	3	Mod & Coding	S	M	2	8	16	8		4	4	32
8	1	7	R		E	E		E	E	E			E		E				Low Power Digital Circuits	4	Mod & Coding	H	M	2	10	20	10		4	4	40





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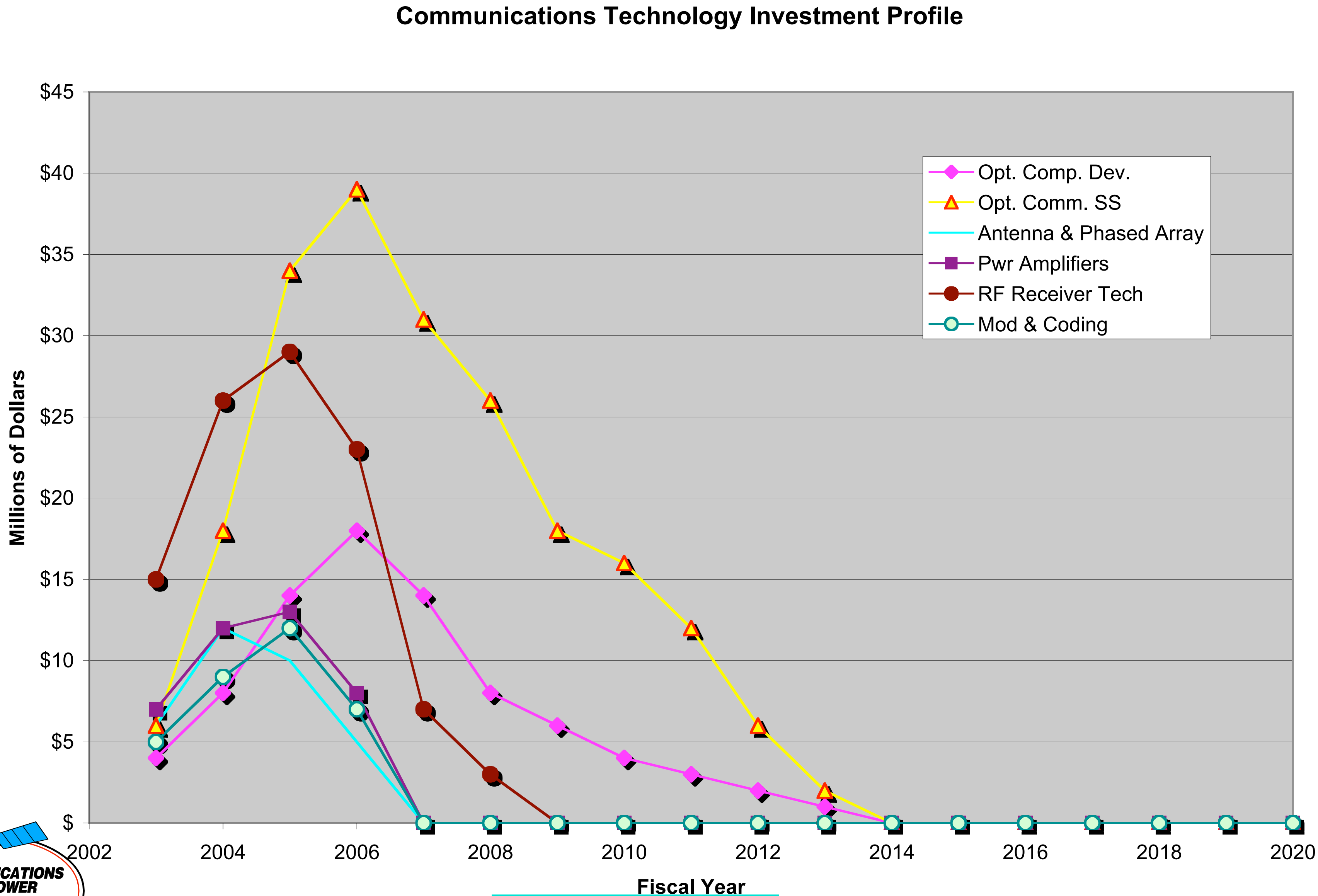
Top Five RF Communications Developments Needed

- **Constant envelope bandwidth efficient modulator**
- **LNAs - Low noise, low bias power at Ka and V-band**

  Technology today: 0.1 InP, single heterojunction, < 1V
- **SSPA power-added efficiency improvements**

  Technology today: 0.1 GaAs, PHEMT single heterojunction, 3-4 V
- **Photonic component maturation**
- **Network Software**

Communications Technology Investment Profile



Section 7: Summary, Recommendations and Phase 3

David Enlow

Presentation Outline

Conclusions

- *Overview*
  - *Completed first level of technology evaluation; optimum selection of technologies requires an integration of mission requirements across future mission sets.*
- *Requirements Definition: Mission and Architectures*
  - *Synergy with PI and "Infrastructure Provider" can yield system development with requirements meshed with science and mission values*
- *Formation Flying Technology Assessment L2015*
  - *SensorWeb could improve all proposed FF missions by providing a common infrastructure*
  - *A broad set of technologies at the mid-TRL levels evaluated which will enable FF and SensorWeb; additional technologies may apply as new missions are integrated with L2015 and SensorWeb architecture evolves.*
  - *Focused technology investment required*

Conclusions

- ***Communications Technology Assessment***
  - ***evolution: RF crosslink performance growth***
  - ***revolution: optical crosslinks becoming more realistic***

- ***On Board Processing vs Communication Bandwidth Trade/ Information Systems (IS) Core Definition***
  - ***advanced processor technology (over current SOA) needed for OBP resource advantage***
  - ***optical crosslinks potential advantage for high data rates***
- ***Integrated Technology Development Trades/Roadmaps***
  - ***Develop a process and exercise the process complete with system modeling, measures of anticipated effectiveness and total system performance to build selection criteria for identifying critical technologies***
  - ***Path of "Critical Investment" is probably wider than subject constrained reality would like***
  - ***Exercise of "get it on paper" forces criteria metrics to be defined, which shape the direction of future technology investment.***

Recommendations

- *Overview*
  - *Select set of key missions to provide breathe of base*
- *Requirements Definition: Mission and Architecture*
  - *Continue interaction of PI with system concept personnel*
- *Formation Flying Technology Assessment*
  - *Long pole technologies are those relative to mission ops of distributed environments.*
  - *More emphasis on OSI layers 1, 2, and 3 to support space networking*
  - *Investigate opportunities for exploiting terrestrial computer networking strategies for space*
  - *Start building SensorWeb system model*

Recommendations

- *Communications Technology Assessment*
  - –*constant envelope BEM development*
  - –*linearized components for efficient, high power amplifiers*
  - –*PAT technologies for high performance optical comm systems*
  - –*standards & interoperability for optical comm*

- *On Board Processing vs Communication Bandwidth Trade/ Information Systems (IS) Core Definition*
  - –*development of advanced processor technology*

- *Integrated Technology Development Trades/Roadmaps Create more formal Taxonomy for Technology Readiness and Insertion*
  - –*Assess limits of evolution*
  - –*need to establish method for Technology Implementation that captures mission breadth*
  - –*Follow emerging "Global" connectivity start-up programs (Sensorcraft, NSSA derivative studies, GPS III, transformational communications study)*

Phase 3 Considerations

Concept/Item	Benefits
Sensor Web Architectures & Technologies Assessment	
Sensor Web Definition & IS Communication Architectures	*Further definition of Sensor Web elements and communications architectures*
Proximity (ad hoc) networks, cluster,UAV-Space links, etc.	*Assessment by modeling and experiment*
Alternative Space Communication Network Assessment (LEO, MEO, GEO)	*Evaluate other space network communications architectures for Sensor Web*
Adjacent Benefit Studies	*Evaluate/Assess Synergy with other USG entities for Space Communications*
Technology Roadmap Development Plan	*Progressive and revolutionary development*
Space Networking Technologies	
Circuit vs Packet Switch Comm Architecture for IP	*Evaluate routing schemes to match limited #s of space nodes/users*
Space suitable Protocols Assessment	*Evaluate protocols that are IP compatible for space*
Routing/Formating Concepts for Space Assets	*Evaluate practical formats and routing methods for space IP*
Space Router/Server Technology Assessment	*Evaluate needs and requirements for space routers and servers*
Communications & IS Component Technologies Assessment/Development	
Space Based Processing	*Increased performance-mass, power & cost advantages*
Ka, V-band Technologies (efficient SSPA, Cooled LNAs, etc.)	*RF Component Development for improved space communications performance/cost metrics*
Optical Communication Technolgies for Space	*Potential for high bandwidth connectivity*

Phase 3 Considerations

Item	Benefit
1. System Definition	Focused effort to establish selection criteria for critical technologies and provide a framework within which to develop a model of SensorWeb the Mission.
2. Mission Classification	Establish need for SensorWeb in terms of future missions. Catalog requirements, profile program time lines, and begin to develop a set of anticipated effectiveness and performance goals for SensorWeb
3. Collateral Stakeholders	Identify other SensorWeb stakeholders who will benefit from access to SensorWeb (space, sub-orbital, and atmospheric) and build an integrated communications picture, e.g. SensorWeb and National Space Security Architecture (NSSA)
4. Build Comprehensive Technology Roadmap	Rank overall system level requirements and establish metrics against those requirements to establish selection criteria to build technology roadmap. Include users, suppliers and operators