25th anniversary
annual INCOSE
international symposium
Seattle, WA
July 13 - 16, 2015

INCOSE
2015

A Systems Engineering Approach to Architecture Development

David A. Di Pietro

Senior Engineer for Advanced Concepts & Architectures

NASA Goddard Space Flight Center, Code 599
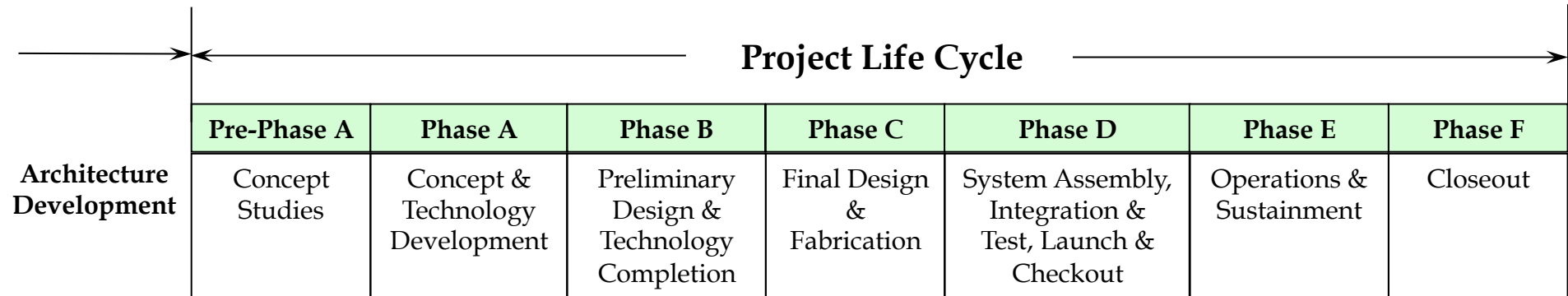
Greenbelt MD 20771

Discussion Objectives

- *Using a simple extension of basic systems engineering (SE) practices*

  1) Describe what a mission area architecture (MAA) is and show how it integrates into a Notional Civil Space (NCS) Architecture Framework

  2) Describe an effective approach for developing an MAA

- *Note: The NCS Architecture is notional and is for illustration & context only – no such architecture has been defined*

  ➢ But, for this discussion imagine there is an NCS architecture

Architecture Studies - Beginning Thoughts

- **Conducted prior to Pre-Phase A of project life cycle**
  - *Scope broader & shallower than scope for concept design studies in Pre-Phase A*

- **Can be conducted at mission area or mission level**
  - ***MAA Studies Address:***
    - *Best-value mix of MAA assets that works collectively in specific scenarios & time frames to accomplish mission area objectives*
    - *Inform planners on recommended capabilities & investment profile across mission area*

  - ***Mission Architecture Studies Address:***
    - *Approaches to meet objectives for single mission*
    - *Done when little is known of mission & significantly different approaches exist*
      - *e.g.,1st time expedition to study moon of Saturn*
    - *Scope narrower & deeper than MAA*
    - *Inform planners on most cost effective approach for mission*

3

Architecture Development Precedes Concept Design in Project Life Cycle
(Fig. 1)

	Project Life Cycle					
	Pre-Phase A	**Phase A**	**Phase B**	**Phase C**	**Phase D**	**Phase E**	**Phase F**
Architecture Development	Concept Studies	Concept & Technology Development	Preliminary Design & Technology Completion	Final Design & Fabrication	System Assembly, Integration & Test, Launch & Checkout	Operations & Sustainment	Closeout

Adapted from NASA Project Life Cycle
NASA Procedural Requirements (NPR) 7120.5E

Architecture Frameworks

- ***Many architecture frameworks reported developed or in use***
  - ➢ *A survey of over 60 frameworks is at iso-architecture.org (see ref. (a)), including those for:*

  - ➢ *Enterprise, defense, information, software, automotive, business, security, etc.*

  - ➢ *Varying scope & taxonomies*

Objective 1

- *Describe what an MAA is and show how it integrates into the NCS architecture framework*

Beginning Definitions

- *Before getting started, just what is an "architecture"?*

  - ➤ *Design?*
  - ➤ *Building codes?*
  - ➤ *Behaviors?*

Beginning Definitions (Cont'd)

- **New Webster Dictionary (1975) defines "Architecture" as:**

    1) *the art or science of building; specif. the art or practice of designing and building structures and esp. habitable ones*

    2) *formation or construction as, or as if, the result of conscious act*

    3) *architectural product or work*

    4) *a method or style of building*

- **New Webster Dictionary (1975) defines "Architect" (from Latin "architectus", from Greek: "architekton" or master builder) as:**

    1) *one who designs buildings & superintends their construction*

    2) *one who plans and achieves a difficult objective (e.g., a military victory)*

8

What is the "NCS Architecture"?

- *From these definitions, it's clear architecting involves some level of design, but*
  - ➢ *What level of design, and is design all there is to it?*
  - ➢ *What does an architecture look like, and what does it do?*

- *To answer these questions for the NCS Architecture, we'll need a common view of:*
  - ➢ *Core elements & constituent MAAs of NCS architecture*

Core Elements of an NCS Architecture

1) The set of ***functional capabilities*** *that characterizes actual or forecast capabilities of NCS physical assets & human command & control (C2) entities*

    - *Includes "what" capability will be delivered along with measures of performance (MOPs), e.g.,*
        - *Quality, quantity, timeliness, interoperability, & robustness (QQTIR) (Note: this is a minimum set of metrics)*

2) The set of NCS ***physical assets*** *(hardware/software) that is, (or is forecast to be) available along with their interconnectivities*

    - *Shows "how" architecture functional capabilities will be delivered*

3) The set of NCS ***human C2*** *operator / decision maker **entities** available along with their interconnectivities*

    - *Note: Automated C2 assets are considered part of physical assets*

10

Core Elements of an NCS Architecture (Cont'd)

4) The concept of operations *(**CONOPS**)* that identifies how NCS physical assets & human C2 entities will be ***employed in time sequence*** to meet a defined mission

    ▪ Used to evaluate effectiveness, etc., as function of environment & scenario

5) The set of ***constraints***, i.e., rules / policies & standards / protocols, that constrain use of NCS assets & human C2 entities

• Each element above pertains to ***specific period in time***, or ***"epoch"***
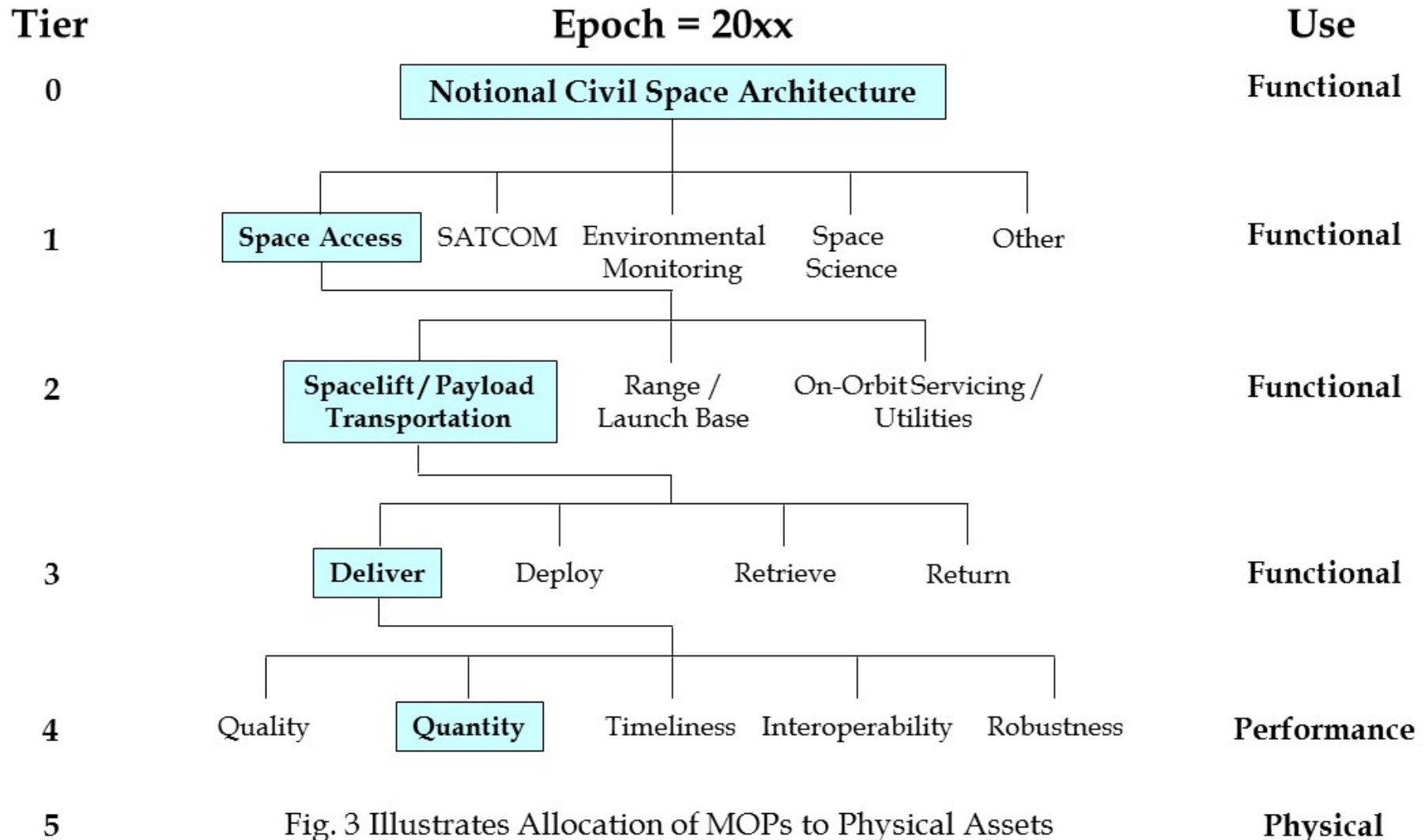
NCS Architecture Framework Example

- **_Framework is established by functional decomposition_**
  - ➤ *Standard systems engineering (SE) technique*

- **_Enables means to identify_**
  - ➤ *Vertical flowdown of guidance*
  - ➤ *Horizontal interfaces within & among architectures*

NCS Architecture Framework Example
Space Access Mission Area Highlighted (Fig. 2)

Tier	Epoch = 20xx	Use
0	**Notional Civil Space Architecture**	Functional
1	**Space Access** SATCOM Environmental Monitoring Space Science Other	Functional
2	**Spacelift / Payload Transportation** Range / Launch Base On-Orbit Servicing / Utilities	Functional
3	**Deliver** Deploy Retrieve Return	Functional
4	Quality **Quantity** Timeliness Interoperability Robustness	Performance
5	Fig. 3 Illustrates Allocation of MOPs to Physical Assets	Physical

Functional Decomposition Example
Space Access Mission Area (Epoch = 20xx)

- ***Tier 0:*** *NCS architecture functions applicable to all mission areas*
  - *Tier 0 represents Enterprise Level*

- ***Tier 1:*** *Allocates Tier 0 functions to mission areas, e.g., provide* ***Space Access***

- ***Tier 2:*** *Allocates Tier 1 functions to sub-mission area functions (e.g., provide* ***Spacelift / Payload Transportation****, etc.)*

- ***Tier 3:*** *Allocates Tier 2 functions to more detailed functions (e.g.,* ***deliver, deploy, retrieve, return,*** *etc.)*

- ***Tier 4:*** *Allocates Tier 3 functions to metrics (**QQTIR**) & **MOPs**, e.g., for "**deliver**" function*
  - *Example quantity metric = x payloads of y,000 kg to z,000 km circular orbit at i°inclination*
  - *Example MOP = 2 payloads of 2,000 kg to 400 km circular orbit at 51.6°inclination (adds specific values)*

- ***Tier 5:*** *Allocates Tier 4 to physical assets & human C2 entities*

Note: Number of tiers can vary among mission areas

Role of Higher Tier Guidance

- *Tier 0: Provides guidance for all mission areas, e.g.,*
  - *Environmental policy (e.g., power / fuel sources, orbital debris, planetary protection, etc.)*
  - *Interoperability standards*
  - *Criticality categories which drive level of robustness (or fault tolerance needed); might pertain to assuring:*
    - ❑ *1) Human survival*
    - ❑ *2) Specific mission operational capabilities*
    - ❑ *3) Specific technology capabilities*

- *Tier 1: Adds guidance unique to each Tier 1 mission area*

- *Note:*
  - *A fault means loss of capability for any reason (component failure, hostile action, etc.)*
    - ❑ *Severity of potential fault can depend on severity of threat*
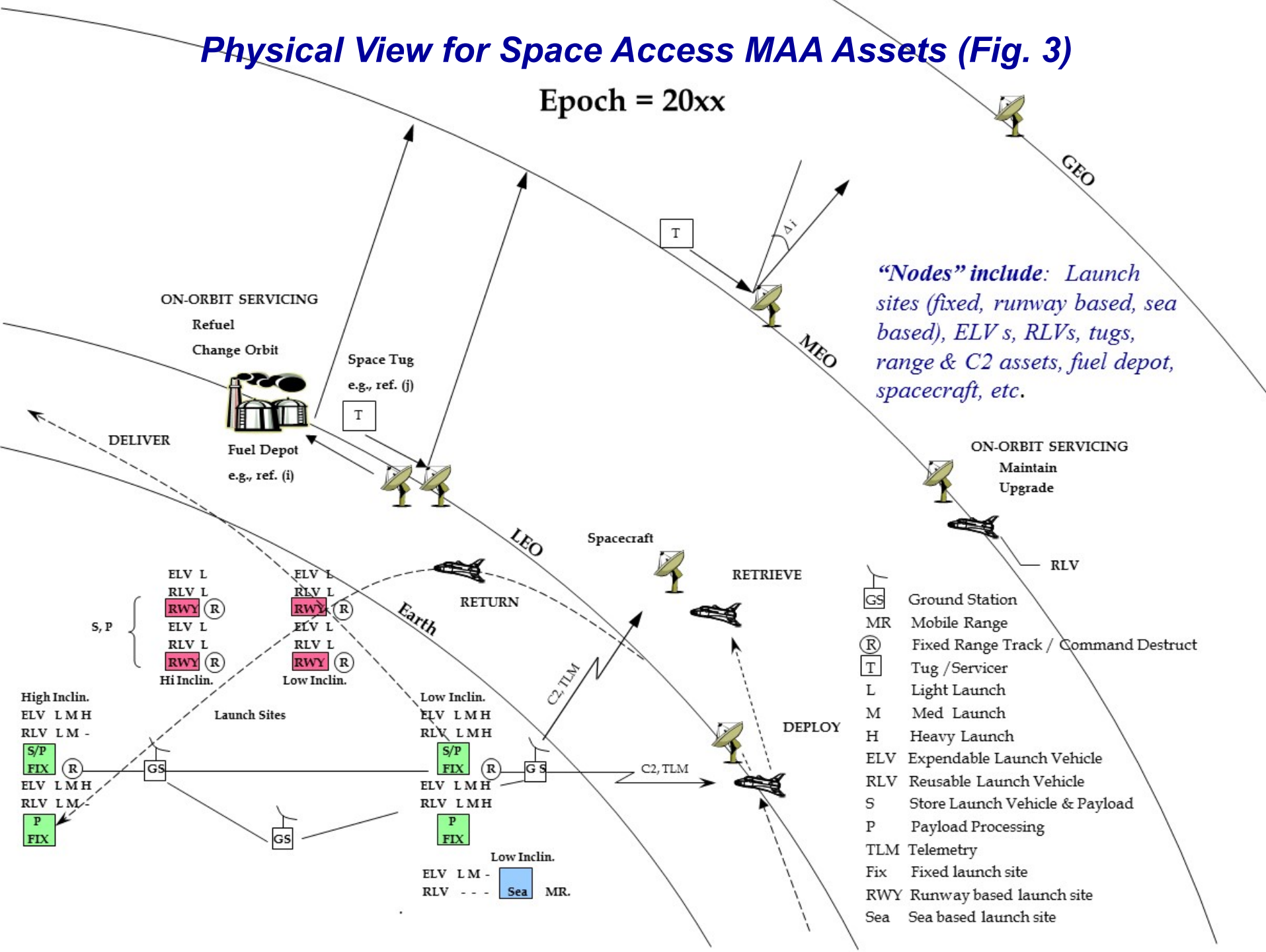
Functional Decomposition Table Example
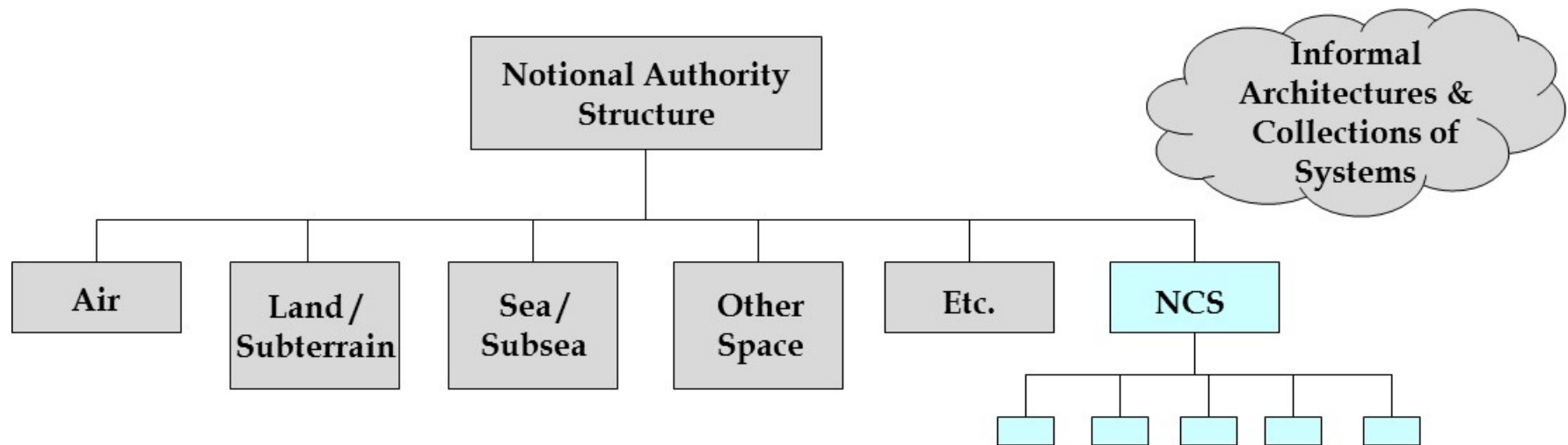## Space Access Mission Area (Epoch = 20xx) (Table 1)

Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
1.0 Provide NCS capabilities	1.1 Provide Space Access capabilities	1.1.1 Provide Spacelift / Payload Transportation capabilities	1.1.1.1 Provide capability to **deliver** payload(s) to orbit	**1.1.1.1.1 Quality**
				1.1.1.1.2 Quantity
				1.1.1.1.3 Timeliness
				1.1.1.1.4 Interoperability
				1.1.1.1.5 Robustness
			1.1.1.2 Provide capability to **deploy** payload(s) on orbit	**1.1.1.2.1 Quality**
				1.1.1.2.2 Quantity
				1.1.1.2.3 Timeliness
				1.1.1.2.4 Interoperability
				1.1.1.2.5 Robustness
			1.1.1.3 Provide capability to **retrieve** payload(s) on orbit	Continue as done for 1.1.1.1
			1.1.1.4 Provide capability to **return** payload(s) from orbit	Continue as done for 1.1.1.1
		1.1.2 Provide Range / Launch Base capabilities	Continue as done for 1.1.1	Continue as done for 1.1.1.1
		1.1.3 Provide On-Orbit Servicing / Utilities capabilities	Continue as done for 1.1.1	Continue as done for 1.1.1.1

Physical View for Space Access MAA Assets (Fig. 3)

Epoch = 20xx

GEO

MEO

"Nodes" include: Launch sites (fixed, runway based, sea based), ELVs, RLVs, tugs, range & C2 assets, fuel depot, spacecraft, etc.

ON-ORBIT SERVICING
Refuel
Change Orbit

Space Tug
e.g., ref. (j)

T

DELIVER

Fuel Depot
e.g., ref. (i)

LEO

ON-ORBIT SERVICING
Maintain
Upgrade

RLV

Spacecraft

RETRIEVE

Earth

RETURN

C2, TLM

DEPLOY

ELV	L	ELV	L
RLV	L	RLV	L
RWY	R	RWY	R
ELV	L	ELV	L
RLV	L	RLV	L
RWY	R	RWY	R
Hi Inclin.		Low Inclin.	

S, P

High Inclin.
ELV L M H
RLV L M -
S/P FIX   R
ELV L M H
RLV L M -
P FIX

Launch Sites

Low Inclin.
ELV L M H
RLV L M H
S/P FIX   R   G S
ELV L M H
RLV L M H
P FIX

C2, TLM

GS

GS

Low Inclin.
ELV L M -
RLV - - -   Sea   MR.

Legend:

GS	Ground Station
MR	Mobile Range
R	Fixed Range Track / Command Destruct
T	Tug /Servicer
L	Light Launch
M	Med Launch
H	Heavy Launch
ELV	Expendable Launch Vehicle
RLV	Reusable Launch Vehicle
S	Store Launch Vehicle & Payload
P	Payload Processing
TLM	Telemetry
Fix	Fixed launch site
RWY	Runway based launch site
Sea	Sea based launch site

NCS Architecture May be Influenced by Other Notional Architectures (Fig. 4)

- *NCS architecture may be part of larger notional collection of architectures that crosses domains & stakeholders*

- *Integration with adjacent architectures may impose additional constraints*

Example Level of "Design" Work in MAA Development

- **MAA technical analysis typically limited to 1st principles**

- **For space access MAA with tugs that maneuver spacecraft, architecture development team (ADT) might size tugs at rocket equation (ref. k) level**
  - *Tug mass might scale to 1st order via rocket equation & other relationships, e.g., dry mass to propellant mass ratio, etc.*

- **No detailed tug subsystem design conducted**

Measures Of Effectiveness (MOEs)

- **MOEs - typically address effectiveness at architecture level & differ from MOPs, e.g.,**
  - ➢ *MOP might pertain to sizing nodes for spacelift, range, & on-orbit servicing functions*
  - ➢ *MOE might pertain to how well these nodes combine to meet an operational scenario at MAA level*

- **MOEs typically need to be decomposed into measurable terms in order to be useable by ADT**
  - ➢ *Need early & continued customer / user engagement to develop & refine*

Architecture Scenarios & Environments

- **Scenarios**
  - *Include driving operational cases at architecture level*

- **Environments typically are assumed conditions in which architecture will be developed & / or operated, e.g.,**
  - *Stable / cooperative vs. unstable / uncooperative governments*
  - *Stable vs. unstable budgets*
  - *Contested vs. uncontested space operations*
  - *Orbital debris / space weather, etc.*

- **Key enabler for NCS architecture level effectiveness analysis**
  - *Consistent scenarios & environments at MAA & NCS levels for given epoch*

Mission Area CONOPS Development & Use

- *Each MAA has at least one CONOPS that applies to a particular scenario, environment, & epoch*
  - ➢ *Used to evaluate MAA effectiveness*

- *CONOPS is specific to architecture design*
  - ➢ *i.e., scenario is met differently by CONOPS using RLVs & on-orbit servicing than by a CONOPS using only ELVs*

    - ❑ *RLV = Reusable launch vehicle*
    - ❑ *ELV = Expendable launch vehicle*

Some Uses for NCS Architecture Framework

- **Provides for structured flowdown of policy & guidance into MAAs**
  - ➢ *Establishes common lexicon for functions, metrics, & products*
  - ➢ *Provides coherent context & relationships among architecture elements*
  - ➢ *Enables horizontal & cross organizational integration within / among MAAs*

- **Allows synthesis of Tier 0 (enterprise) architecture from constituent MAAs for given epoch**
  - ➢ *Facilitates identifying Tier 0 CONOPS & evaluating Tier 0 architecture effectiveness*

- **Exposes gaps / overlaps indicating need for follow-on MAA studies**

- **Highlights whether studies are for:**
  - ➢ *a) One mission area across all QQTIR metrics*
  - ➢ *b) All mission areas for only one metric, e.g., timeliness*

Objective 2

- ***Describe an effective approach for developing an MAA***

Terms of Reference (TOR)

- **TOR identifies**
  - *Who, what, where, why, when of study process & products*
    - *Incl. resources, participants, roles & responsibilities*
- **TOR typically will include**
  - *Problem background (incl. relationship to relevant past studies)*
  - *Problem statement: Concise & clear*
  - *Study scope & product depth, i.e.,*
    - *Functional boundaries (e.g., include spacelift, exclude on-orbit servicing)*
    - *Stakeholders*
    - *Domains*
    - *Epoch*
    - *Mission area guidance (e.g., relevant policy directives, etc.)*
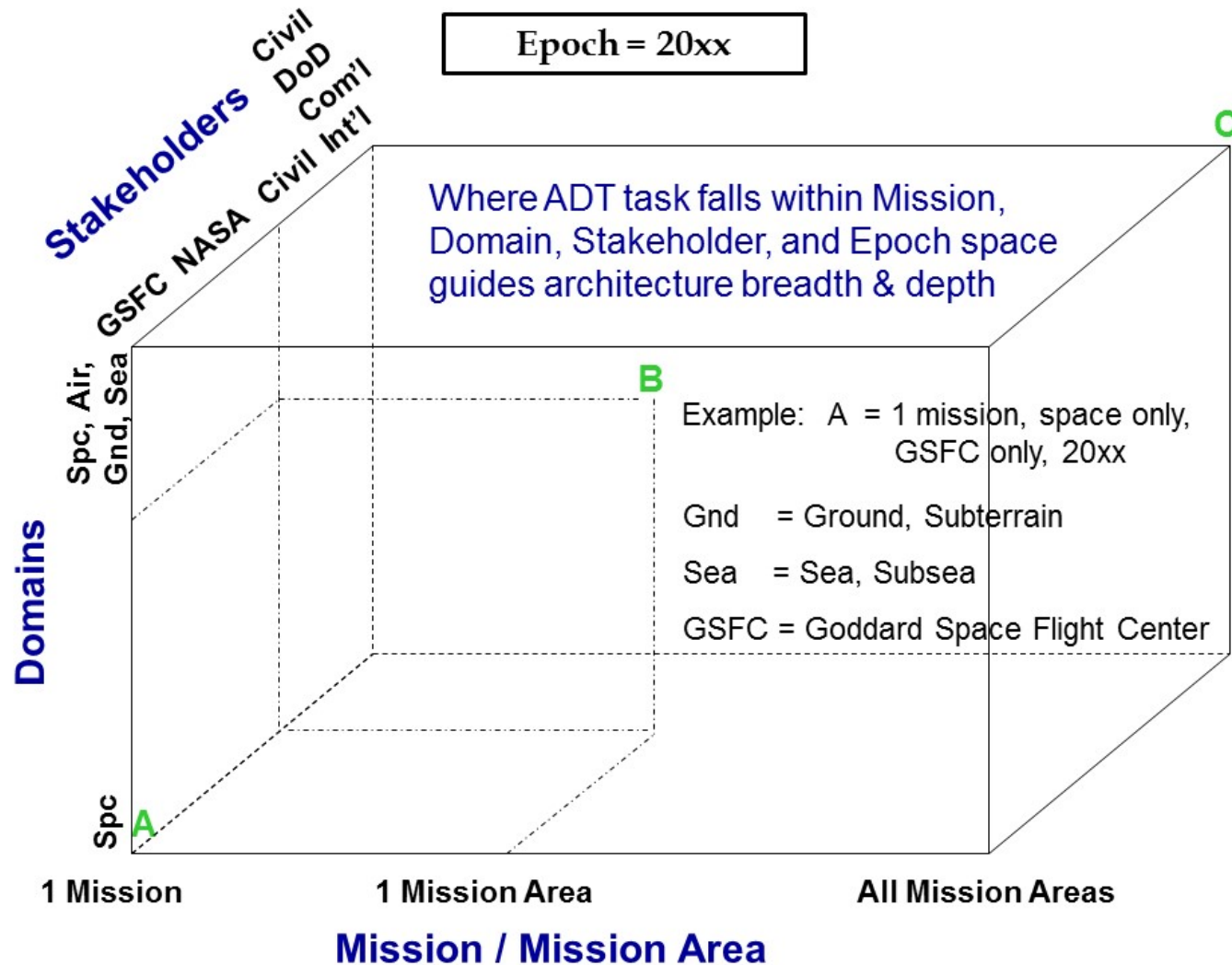 - *Guidance for establishing MOEs*
  - *Definitions for key unique terms*

Terms of Reference (TOR) (Cont'd)

➢ *Assumptions, Constraints, Groundrules*
  - ❑ *System (x) from stakeholder (y) is out of scope*
  - ❑ *Use data from source (z) as principal input*
  - ❑ *Scenarios & environments*
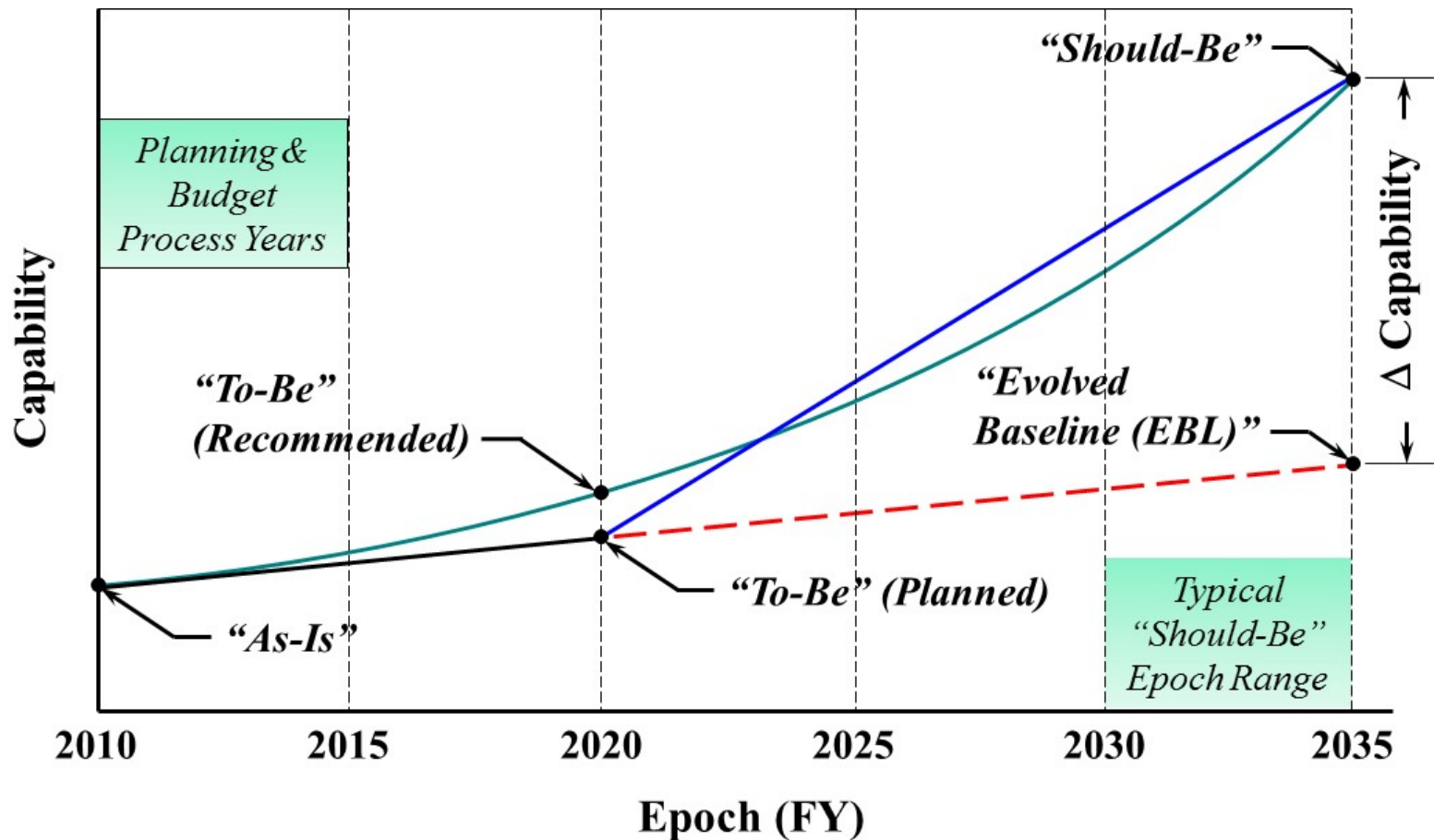 - ❑ *Technology readiness date*
  - ❑ *Policy, Cost*

➢ *Guidance on how to select recommended architecture*
  - ❑ *e.g., single, best value architecture within cost constraint, etc.*

- **TORs are deceptively difficult, but worth time to develop well**

  ➢ *Weak TOR can delay product delivery*
    - ❑ *Can leave ADT to define purpose, scope, depth, epoch, products while designing MAA*
    - ❑ *ADT view may not match customer view*

Epoch = 20xx

Stakeholders — Civil, DoD, Com'l, GSFC NASA Civil Int'l

Domains — Spc, Air, Gnd, Sea

Where ADT task falls within Mission, Domain, Stakeholder, and Epoch space guides architecture breadth & depth

Example: A = 1 mission, space only, GSFC only, 20xx

Gnd   = Ground, Subterrain

Sea   = Sea, Subsea

GSFC = Goddard Space Flight Center

Spc — A

1 Mission   1 Mission Area   All Mission Areas

Mission / Mission Area

"As-Is", "To-Be", "Should-Be", & "Evolved Baseline" MAAs* (Fig. 6)

Adapted from model used by ref. (l)

Conducting Effective Architecture Studies

- *Lets now look at <u>one way</u> to effectively conduct an MAA study*
  - ➤ *A generic, iterative "design cycle" process*

- *Important Note:*
  - ➤ *MAA studies can be conducted more than one way*

Introduction to Design Cycle Process for Architecture Studies

- **Design cycle process is structured, iterative approach**
  - ➢ *Based on standard SE technique for conducting requirements development, design, & analysis*
  - ➢ *Brings products to common, coherent reference point in each cycle*
    - ❑ *Maintains synchronization of assumptions, trades & analyses*
    - ❑ *Accelerates start of architecture design*
    - ❑ *Provides discrete opportunities for stakeholder / management review*
    - ❑ *Facilitates systems level integration*
    - ❑ *Improves final report & reduces work required to produce it*

- **Other process models (e.g., waterfall, ad-hoc iterative, etc.), less effective for studies with high uncertainty**
  - ➢ *Waterfall (i.e., linear, unidirectional) processes more effective for tasks that are well understood*
  - ➢ *Ad-hoc iterative processes difficult to keep synchronized*

Introduction to Design Cycle Process for Architecture Studies (Cont'd)

- *First time MAA developments are inherently exploratory & uncertain*
  - *Teams learn at high rate*
  - *Unknown-unknowns often emerge as byproduct of design work*
    - *Can't be planned for in advance*

- *Can't plan all study details at outset*
  - *Outline general plan (incl. major activities & milestones) early*
  - *Develop schedule template for each design cycle*
    - *Allows cycles to be moved & tailored, to minor extent, within general plan*

- *Starting design work early accelerates learning*
  - *Surfaces unknown-unknowns early*
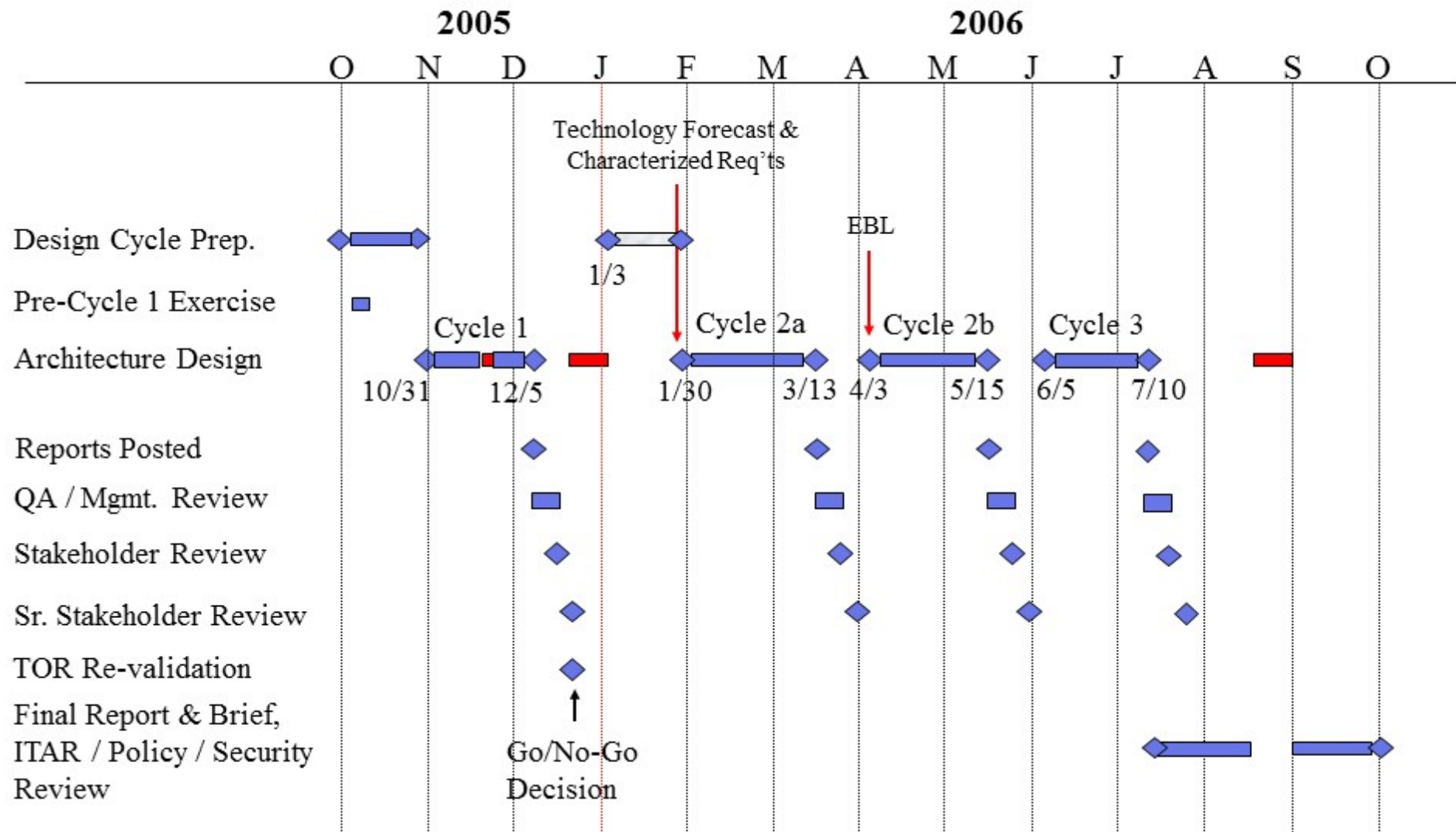 - *Allows adjustments when there is still time to resolve*

Design Cycle Approach Overview
Conducted in 3 Cycles

- ***Cycle 1: Pathfinder; learn & assess readiness for design***
    - ❑ *a) "requirements" characterized in form usable for analysis*
    - ❑ *b) metrics compatible with modeling tools*
    - ❑ *c) modeling tools can analyze design to provide desired product set*
    - ❑ *d) desired product set suffices to answer problem statement in TOR*
    - ➢ *Analyze a few architectures that span solution space*
    - ➢ *Surrogates can be used for "requirements", technology forecast*
- ***Cycles 2a & 2b:***
    - ➢ *Conduct comprehensive investigations for broad range of candidate architectures*
    - ➢ *Determine most promising architectures across trade space*
- ***Cycle 3:***
    - ➢ *Refine designs & analyses on most promising representative architectures of solution space*
    - ➢ *Recommend single architecture based on criteria in TOR*

12-Month MAA Study Design Cycle Template
CY 2005/2006 Example with Pre-Design Products Available (Fig. 7)

Pre-Design Products
Draft Products Developed before Cycle 1

- **Pre-Design Products Accelerate Cycle 1 start**
  - *Functional decomposition through performance metrics*
  - *Generic scalable physical nodes*
    - *Prepare for modeling use, incl. governing equations / relationships*
  - *Generic "threads" (see next chart)*
  - *Types of modeling tools available to analyze nodes*

  - *Technology forecast (to degree readily available in roadmaps, etc.)*
  - *MOEs previously used or identified for mission area*
  - *Summary of known mission area guidance & relevant studies*

- **Pre-design products may also include**
  - *Data collection templates that support development of technology forecast and "as-is", "to-be" (planned), & EBL architectures*

Architecture Trade Case Matrix
Space Access Example

- **Analyses of individual nodes combine to determine performance / effectiveness of "threads"**
  - *Threads contain all nodes needed to deliver an end-to-end service, e.g.,*
    - *Deliver payload to orbit includes nodes for: launch base, ground station, range, launch vehicle, human C2 entities*

- **Analyses of individual "threads" combine to determine performance / effectiveness of MAA**
  - *ADTs assign combinations of threads to a range of candidate MAAs*

- **Functional decomposition for final MAA solution transferred into NCS functional decomposition table**
  - *Formats similar*

25th anniversary
annual INCOSE
international symposium
Seattle, WA
July 13 - 16, 2015

Architecture Trade Case Matrix
Leverages Functional Decomposition Table Format (Table 2)

Space Access Example, Epoch = 20xx

Architecture Solution (How's) => Functions / MOPs (What's)	1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c	5a	5b	5c	6a	6b	6c
Provide Space Access Capabilities																		
Provide Spacelift / Payload Transportation Capabilities	All ELV			Mix ELV / RLV			All RLV w/Tugs											
- Deliver																		
- Quality										Each "architecture" is a composite of several "threads" designed to meet MOPs							
- Quantity																		
- Timeliness										Architecture #1 represents an all ELV solution where threads 1a, 1b, & 1c might include light, medium, & heavy ELVs, respectively.							
- Interoperability																		
- Robustness										Architecture #3 represents an all RLV solution with tugs, where threads 3a, 3b, & 3c might include light RLVs, medium RLVs, & medium tugs, respectively.							
- Deploy (QQTIR as above)																		
- Retrieve (QQTIR as above)																		
- Return (QQTIR as above)																		
Provide Range / Launch Base Capabilties										Expand as done for Spacelift / Payload Transportation							
Provide On-Orbit Servicing / Utilities Capabilities										Expand as done for Spacelift / Payload Transportation							

36

Product	Cycles
User Needs / "Requirements" Classes & Bounding Cases	*, 2a, 2b, 3
Scenarios	1, 2a, 2b, 3
Future Environments / Threat Assessment	1, 2a, 2b, 3
CONOPS	1, 2a, 2b, 3
Doctrine / Policy Assessment	1, 2a, 2b, 3
Functional Decomposition (incl. MOPs / Interface "Req'ts")	1, 2a, 2b, 3
Tradespace & Trade Case Matrix	1, 2a, 2b, 3
Architecture Alternative Point Designs	1, 2a, 2b, 3
"As-Is", "To-Be" (Planned), & EBL Architectures	2b, 3
Technology Forecast	*, 2a, 2b, 3

Note: Shading aggregates products into ADT subteam reports

1) Operations: Green shading
2) Systems: Blue shading
3) Analysis: Yellow shading
4) Architecture SE: Grey shading

* Surrogates may be used for Cycle 1

37

Product	Cycles
MOEs	1, 2a, 2b, 3
Performance / Utility Analyses	1, 2a, 2b, 3
Vulnerability Assessment	1, 2a, 2b, 3
Work Breakdown Structure	1, 2a, 2b, 3
Cost Analysis	1, 2a, 2b, 3
Risk Assessment	1, 2a, 2b, 3
Subteam Technical Reports	1, 2a, 2b, 3
Systems Engineer Report	1, 2a, 2b, 3

Some Additional Recommended Practices for MAA Development

- **Set "Should-Be" epoch far enough out for candid discussion**
  - *25 years: Allows candid discussion of future architecture*
  - *15 years: Discussion highly constrained by current budget*
- **Keep Cycle 1 short, but apply concerted effort**
  - *Avoid pressure to use results from Cycle 1 for budget inputs*
- **Don't retrofit architectures from prior cycles**
  - *Just apply what's been learned to future cycles*
- **Exercise full solution space in Cycles 1, 2a & 2b**
- **Start writing ADT report in Cycle 1, refine in Cycles 2 & 3**
  - *Write reports first (documents of record), then translate to briefings*
- **Remain impartial**

Closing Thoughts

- *Approach presented uses simple extension of SE that can help ADTs, their customers, & stakeholders:*
  - *Quickly understand core elements of an enterprise architecture when planning for far-term future*
  - *Visualize how constituent MAAs might get developed & integrated into an enterprise architecture*

- *As approach is based on widely understood SE techniques & terminology, it should:*
  - *Be readily usable by wide range of teams without need for special training in more complex & abstract methods*
  - *Have application beyond space architecture development*

Questions ?

References

- **a) iso-architecture.org. 2014. "Survey of Architecture Frameworks."** Last accessed 3 September 2014. http://www.iso-architecture.org/ieee-1471/afs/frameworks-table.html.

- **b) Di Pietro, David A. 2009. "National Security Space (NSS) Architecture Development Process (Draft)."** Briefing to Mr. J. Rouge, Director National Security Space Office, Washington, DC (US). Presented and approved 9 February.

- **c) Di Pietro, David A. 2009. "Space Mission Architecture Development, Notional Framework and Approach."** Training course presented at the NASA Goddard Space Flight Center, Greenbelt, MD (US). 30 September.

- **d) Di Pietro, David A. 2014. "A Systems Engineering Approach to Architecture Development."** Briefing presented (http://www.dtic.mil/ndia/2014system/2014system.html) at the National Defense Industry Association 17th Annual Systems Engineering Conference, Springfield, VA (US). October 2014.

- **e) NASA Headquarters. 2012. NASA Procedural Requirements (NPR) 7120.5E w/Changes 1-10.** NASA Space Flight Program and Project Management Requirements, Figure 2-5. Washington, DC (US): Office of the Chief Engineer.

References (Cont'd)

- *f) Razzaghi, Andrea I., Di Pietro, David A., Simon-Miller, Amy A., and Spencer, John R. 2007. Enceladus Flagship Mission Concept Study, Revision 1, Edited for Public Release.* NASA Goddard Space Flight Center, Greenbelt, MD (US). 2 November.

- *g) Razzaghi, Andrea I., Di Pietro, David A., Quinn, David A., Simon-Miller, Amy A., and Tompkins, Stephen D. 2008. "Mission Concepts for Studying Enceladus."* Paper presented at Space Technology & Applications International Forum, Albuquerque, NM (US). 14 February.

- *h) G. & C. Merriam Co. 1975. Webster's New Collegiate Dictionary.* Springfield, MA (US).

- *i) Wikipedia. 2014. "Propellant_depot." Last accessed 5 October 2014.* http://en.wikipedia.org/wiki/Propellant_depot.

- *j) Wikipedia. 2014. "Space_tug." Last accessed 5 October 2014.* http://en.wikipedia.org/wiki/Space_tug.

- *k) Brown, Charles D. 1998. Spacecraft Mission Design. 2nd Edition.* Equation 3.21. Reston, VA (US): American Institute of Aeronautics and Astronautics.

References (Cont'd)

- **l) Hagemeier, Hal E. 2009. Deputy Director, National Security Space Office.** *Washington, DC (US).*

- **m) Rader, Andrew A., Ross, Adam M., and Fitzgerald, Matthew E. 2014. "Multi-Epoch Analysis of a Satellite Constellation to Identify Value Robust Deployment across Uncertain Futures."** *Paper presented (http://seari.mit.edu/publications.php#2015) at AIAA Space 2014, San Diego, CA, August 2014.*

Backup Charts

Interface Identification

- *Horizontal interfaces (within or among MAAs) can be highlighted on functional decomposition*
  - ➢ *e.g., transmit data rate / frequency from remote sensing node (Environmental Monitoring MAA) to ground station (SATCOM MAA)*

- *Some physical interfaces may need to be standardized*
  - ➢ *e.g., for some on-orbit servicing nodes*

- *Horizontal integration analyses across MAAs validate interfaces are compatible*

Analyses may be simplified when closely related user needs / "requirements" points are approximated by representative points, e.g., A, B, & C

Three MOP axes are shown here for illustration; a trade space will typically contain many MOPs

	D/D	RTN	OOS
A	Light	None	None
B	Light	Med	Med
C	Heavy	Heavy	Heavy

On-Orbit Servicing (OOS)
None Lgt Med Hvy

Return (RTN)
None Light Med Heavy

Deliver / Deploy (D/D)
None Light Med Heavy