NASA Integrated Network Monitor and Control Software Architecture

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The National Aeronautics and Space Administration (NASA) Space Communications and Navigation office (SCaN) has commissioned a series of trade studies to define a new architecture intended to integrate the three existing networks that it operates, the Deep Space Network (DSN), Space Network (SN), and Near Earth Network (NEN), into one integrated network that offers users a set of common, standardized, services and interfaces. The integrated monitor and control architecture utilizes common software and common operator interfaces that can be deployed at all three network elements. This software uses state-of-the-art concepts such as a pool of re-programmable equipment that acts like a configurable software radio, distributed hierarchical control, and centralized management of the whole SCaN integrated network. For this trade space study a model-based approach using SysML was adopted to describe and analyze several possible options for the integrated network monitor and control architecture. This model was used to refine the design and to drive the costing of the four different software options. This trade study modeled the three existing self standing network elements at point of departure, and then described how to integrate them using variations of new and existing monitor and control system components for the different proposed deployments under consideration. This paper will describe the trade space explored, the selected system architecture, the modeling and trade study methods, and some observations on useful approaches to implementing such model based trade space representation and analysis.

I. Introduction

Driven by requirements to provide its users with an integrated network offering common services, to improve the level of system integration and re-use, and to reduce operations costs through higher level of automation, the

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National Aeronautic and Space Administration (NASA) Space Communications and Navigation (SCaN) office has been studying a number of candidate integrated space communications system architectures. SCaN's three existing network elements, the Deep Space Network (DSN), Space Network (SN), and Near Earth Network (NEN),have evolved independently since their initial deployment, starting more than 45 years ago. When users only need one of these three network elements having separate service types and interfaces has not been a major problem. Some users apparently prefer to have simple, socket, or even radio frequency (RF), interfaces that meet only their minimum requirements for data delivery. However, for the 20-30% of users who have on-going requirements for more than one network element, and sometimes for all three, it is challenging to obtain services in a consistent way. Reducing the added complexity for these users, as well as responding to SCaN's programmatic requirements to modernize its services, provide new capabilities, including common, internationally interoperable interfaces and space internetworking, and reducing operational costs are the primary drivers to move toward a more integrated future architecture.

The SCaN Integrated Network Architecture (INA) is essentially a System-of-Systems (SoS), to be composed of the three existing networks. To represent this integration, these three networks are now referred to as elements of the INA: the Deep Space Element (DSE), the Earth Based Relay Element (EBRE) and the Near Earth Element (NEE). A series of Analysis of Alternative (AoA) trade space studies have been conducted to analyze this problem and to successively prune the possible trade space. The details of this new architecture, and the outcome of the first several cycles of trade studies have been reported separately at this conference in the paper "NASA Integrated Space Communications Network" by Tai, Wright and Bhasin[1]. This paper will describe the specific study cycle that explored the integrated network monitor and control software architecture, present the selected Network Control Software (NCS) system architecture, describe the modeling and study methods, employed and offer some observations on useful approaches to doing such model based trade space representation and analysis.

A model-based system engineering (MBSE) approach using the Systems Modeling Language (SysML™)[2] for representation was adopted by the trade study team to define, at a sufficient level of detail, several options for implementing the network monitor and control architecture. A multi-center team drawing on modeling expertise and Subject Matter Experts (SME) from three NASA centers, Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and Glenn Research Center (GRC) performed this study. The SysML™ model was used to describe the integrated system, to evaluate the candidate architecture alternatives, and to support the costing of the four different software options. This trade study modeled the three existing self-standing network elements at Point of Departure, (PoD, roughly the expected states of the network elements by 2015) and then described how to integrate them using various combinations of new and existing monitor and control system components for the four candidate deployments.

II. Architecture Trade Study Overview

A set of trade study cycles has been defined to deal with a broad range of optimization topics for the SCaN Integrated Network. The problem is inherently one of system-of-systems design and optimization. The studies have dealt with topics like the level of integration, level of hardware / software commonality, physical deployment (distribution / centralization), system operability, and ease of use. A core challenge is that there are very different mission and operational models, and different kinds of physical communications assets, in the three network elements. The communications assets in the EBRE (Tracking Data Relay Satellite (TDRS) spacecraft and essentially static ground stations), the NEE (small-medium antennas with a fast slew rates for near Earth communications), and DSE (large, but slow moving, antennas for deep space with sensitive receivers and powerful transmitters) are distinct and focused on their particular communications regimes. In addition to addressing how to integrate these diverse assets, each cycle of trade studies has investigated one or more major topics and then recommended an outcome (possibly with variations), which pruned the trade space. The initial trade space study cycles cover:

- Cycle 1: Evaluate vastly different physical deployments of service execution and integrated network management system elements, highly centralized vs highly distributed; evaluate COOP impacts
- Cycles 2-3: Evaluate different network control software / system architectures, evaluate COOP and security impacts; evaluate different network control team organizations
- Cycles 4-5: Evaluate different planning and scheduling system approaches; evaluate different planning and scheduling team processes and organizations

The results of each cycle have fed forward into the next, and at each successive step the previous cycle's results were adopted as a baseline. Each cycle of studies also adopted stated assumptions about elements external to the study focus until those system elements could be studied in turn. This paper discusses the data system architecture results, methods used, and observations from, the Cycle 2-3 study.

Each of the trade spaces are inherently multi-dimensional, involving three separate network elements, each with its own PoD architecture and each including with multiple candidate future options that typically ranged from those are very similar to PoD, i.e. as-is architectures, to those that are very different from the current architecture..

Each of the trade study cycles was initiated by producing a guiding document that typically covered the following topics in a compact form:

1. An overall process flow for the trade study
2. A description of each of the separate parts of the study e.g., software, hardware, operations
3. Statement of the purpose and objectives of each part of the trade study
4. Any assumptions and constraints
5. The scope of the study, typically related to the baseline functional overview
6. Description of how the network and system elements mapped into the trade study
7. Definition of the trade space options to be considered
8. Description of the approach to be used for the trade study
9. Team composition, duration, and planned schedule for the effort

The results of each of the trade studies have been documented in a combination of presentation materials, SysML™ models, costing spreadsheets, and a trade study end of cycle report. Each of the cycles has also had at least two reviews by two separate boards, one composed of SCaN leadership and a second one composed of stakeholders from the network elements and the mission user community.

The Cycle 1 trade space models used a combination of presentation diagrams (in PowerPoint™) to model the system options and Excel spreadsheets to do the costing. PowerPoint™ is convenient and familiar, but its limitations for doing complex system modeling quickly became evident. Any changes anywhere in the "model", to use the term very loosely, caused changes to that had to be propagated throughout the set of slides. This was an entirely manual effort that was found to be highly subject to transcription errors and prone to discrepancies. As a modeling tool it offers no framework or support other than drawing objects.

Starting with the Cycle 2 studies, in March 2011, the team agreed to adopt SysML™ and to use a common implementation of it NoMagic's MagicDraw™ modeling tool. A Teamwork server was set up where it would be securely accessed from anyone at a NASA center. This adoption of a common toolset and a "single-source-of-truth" model repository was essential to support the work of the distributed, multi-center, team. The goal of this modeling effort was to develop sufficiently accurate system hardware and software representation models (using SysML™'s Block Definition Diagrams and Internal Block Diagrams) to clarify understanding of the options, support analysis of alternatives, and support costing efforts. This involved producing PoD and integrated network models for the identified options. Operations functional models (using SysML™ activity diagrams) that relate to the system models were also developed, but these are described separately. A secondary intent of this modeling effort has been to support evolution of the architecture models to support future study cycles and to provide some level of objective analyses of model completeness and complexity.

III. Network Monitor and Control Architecture Trade Study

A. Initiate the Trade Study Cycle

The outcome of Cycle 1 was to adopt a common set of Integrated Service Execution (ISE) hardware and software derived from the next generation EBRE system development that is now underway, called the SN Ground Segment Sustainment (SGSS) Project. The selected option, ISE-1, assumes that each ground station site, with one or more antennas, will have a pool of re-programmable equipment that acts like a configurable Software Defined Radio (SDR) and will do data delivery using Consultative Committee for Space Data Systems Space Link Extension (CCSDS SLE)[3] and Cross Support Transfer Services (CSTS)[4] services directly to and from the ground station site to the users. This system architecture also includes a hierarchically distributed monitor and control framework, along with centralized network scheduling and planning. As with each of these trade studies there remain some open questions regarding suitability of this architecture for all of the operational domains of interest. In this case a key issue is applicability of this particular SDR approach for sensitive, low SNR, deep space signal processing.

The Network Control Software (NCS) study assumed the ISE-1 outcome from the first cycle and that some form of centralized service management (planning, scheduling, and user interface portal) would be adopted. The details of this were deferred to the next trade study, Cycle 3-4. The scope of the NCS trade study, Cycle 2-3, was to:

- Assess the benefit of common software for network monitor and control of the three SCaN network elements.
- Determine the optimum degree of commonality for the network monitor and control software.
- Assess the potential use/reuse of the EBRE developed network monitor and control software for the other two SCaN network elements: NEE and DSE.

For the network monitor and control architecture study four different trade space options were identified, as shown in Table 1. These are differentiated by the degree of integration and commonality of software, they range from use of a common network control framework, to common interface software, to protocol translating gateway approaches.

Table 1: Network Control Software Option Descriptions

Software Alternatives		Description
Option 1 (NCS-1)	Common network control framework	Common software framework for the entire network control functionalities across all network elements, i.e., EBRE, NEE, and DSE. Such a software framework includes common code providing generic network control functionality, but can be selectively adapted or specialized by network elements, thus accommodating network asset-specific functionality.
Option 2 (NCS-2)	Common network control interface	Common software components (within the network control function) that provide the interfaces with human operators, service management, and user mission elements.
Option 3 (NCS-3)	Central gateway	A singly implemented and centrally deployed gateway that functions as the single interface point (for the network control function) with the service management and user mission elements. The gateway performs necessary protocol conversions for the dissimilar and network asset-specific network control interfaces at the various network elements, i.e., EBRE, NEE, and DSE.
Option 4 (NCS-4)	Network element gateway	Multiply deployed gateways that function as the interface points (for the network control function) with the service management and user mission elements through common interface protocols. The gateway at each network element, i.e., EBRE, NEE, and DSE, performs necessary protocol conversions for the dissimilar and network asset-specific network control interfaces in each element.

For each of these options a simple diagram was produced to describe how these options differ. Having this model was an important reference for the whole team because it was familiar and represented a high level point of agreement regarding system decomposition for each option. Figure 1 shows an evolution of the initial model that was produced in order to more clearly identify the Network Control interfaces. The model includes other elements than just Network Control, but the focus is upon those elements within the red dashed line.

In this diagram the color-coding is significant. The Service Execution elements look nearly identical because this is the ISE-1 conclusion. The Service Execution elements are all derived from the EBRE upgrade project. The embedded green, yellow, and grey parts identify the asset specific elements for the DSE, EBRE, and NEE. In NCS-1 adoption of a common network control framework is assumed, but an instance is deployed in each network element. In the other three options, use of much of the existing asset specific NCS subsystems is assumed (green, yellow, grey), but different methods of interfacing these to the central service management and to the common service execution is assumed.

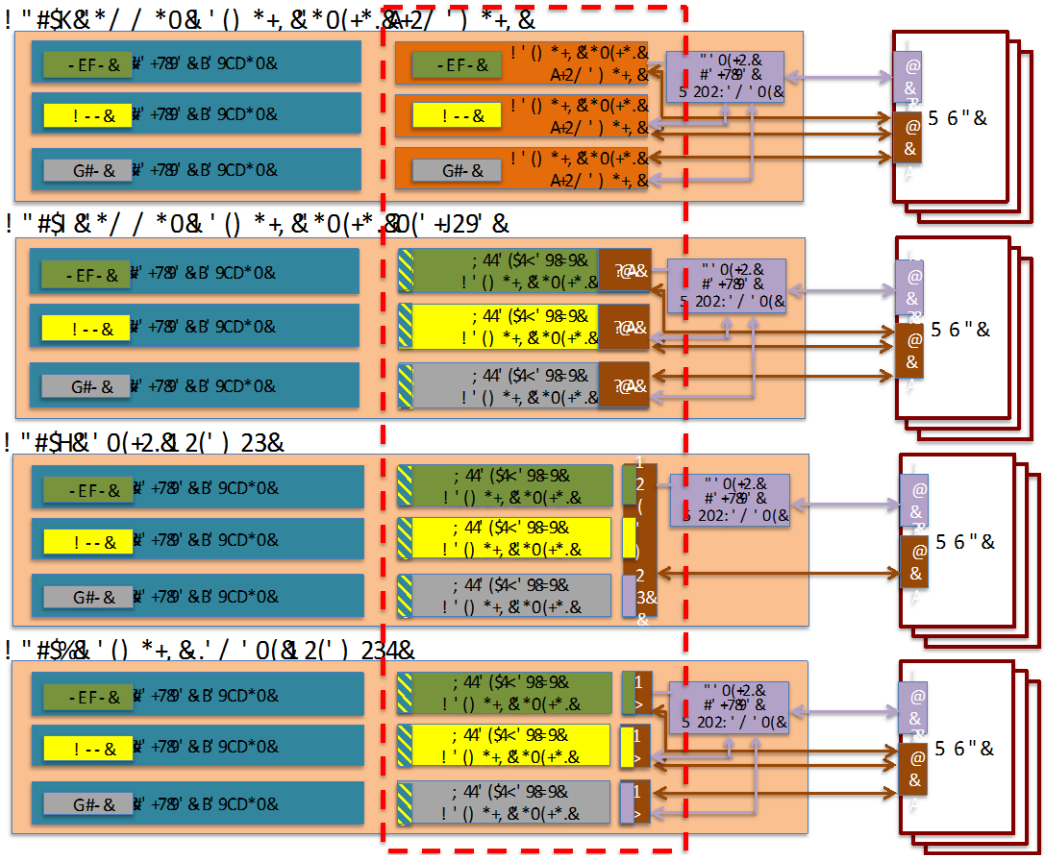

Figure 1. Integrated Network Control Software Architecture – System Context Per Options

B. Gather the Requirements and Background Materials

A key aspect of the network control trade study was to divide the task into three separate, parallel, but related activities: common network monitor and control software; integrated network monitor and control process; and integrated network monitor and control team structure. Only the first of these trade study activities is described in this paper.

As a form of requirements gathering the whole trade study team started by surveying and then analyzing the mission and operational drivers on the existing systems:

- Identify key mission operations drivers associated with different mission domains:
  - Sub-orbital, Low Earth Orbit (LEO), Geosynchronous Earth Orbit (GEO), Highly Elliptical Orbit (HEO), Lunar, Deep Space, Robotic Exploration, Human Exploration
- Identify key characteristics of network monitor and control (in operational aspect) at three network elements present and future.
- Assess commonality, differences, similarities, and dissimilarities for network monitor and control operations among the three network elements.
  - Analyze software ramifications
  - Analyze operational process ramifications

C. Define the Modeling Approach

The Cycle 1 study had used Microsoft PowerPoint™ and the benefits and issues of that that approach were well understood. However, because of the complexity of this trade study, and because there was a belief within the team that a model-based approach would prove valuable we agreed to adopt this formal approach for this study cycle. The goals for the modeling effort were to:

- Identify how to develop models that would support the trade study; and
- provide sufficient design clarity; and
- permit maximum re-use of elements.

Two of the three centers had already invested in the MagicDraw™ UML tool and the Teamwork model repository. There was also an existing level of expertise at these two centers. Because of this, it was the obvious choice.

However, the two groups of modelers had each adopted different UML profiles: one had been using the UPDM profile (based on DoDAF and MoDAF)[5] and the other had been using the SysML™ profile. While the UPDM profile works well for operational models and high level views of architectures, its limitations for doing more detailed system and software views in this SoS trade space quickly became problematic. After some trials, an early decision was made to abandon UPDM and to produce a SysML™ based model decomposition hierarchy that includes stereotyped system decomposition (system, system element, subsystem, SW module, SW component, SW unit) and operational decomposition elements (ops function, activity, task, action). In the system decomposition hierarchy, below the subsystem level, there are also hardware elements parallel to the software ones (HW configuration item, HW component, HW unit). A common set of color codes was also adopted in the model to enable discrimination among components belonging to different system elements and to distinguish new and modified components from existing ones. In the PoD diagrams the service management systems, for planning and scheduling, are shown as a yellow-green, the network control systems as a golden yellow, and the service execution systems as a blue-green. The modified versions are shown respectively as a darker green, orange, and purple.

The architecture model itself is structured into three main parts:

1. An information model with data objects and data structures
2. A model library with a hierarchically decomposed set of components that could be instantiated, assembled, generalized, and specialized as needed
3. A set of trade space options that each had their own multi-level decomposition with multiple views for overall system structure, element structure, logical composition, system deployment, and data and control flows

While SysML™ provides a very good set of general modeling and representational primitives, it provides little guidance in how to define suitable views on the system, especially for the SoS trade space models. To rectify this deficiency the functional, connectivity, and information views defined in the Reference Architecture for Space Data Systems (RASDS)[6] were used to guide the development of suitable viewpoint specifications. In particular, the following diagram types and objects were used to create the model views:

- System software structures and data / control flows (function BDD structure and IBD composition)
- System and software product line / variation points (function BDD generalization and specialization)
- System deployment across multiple sites (site and function BDD showing allocation)
- Software functional abstractions (abstract function activity and BDD generalization and specialization)
- Information models (information object BDD)

D. Define the Point of Departure Architectures

In order to model and compare the candidate NCS architecture options a sufficiently accurate model of the PoD architectures of all three network elements was required as a baseline. NCS-1 essentially presumes wholesale adaptation of the new EBRE architecture; NCS-2 presumes adaptation of the ERBE developed operator environment and integration with the evolved PoD asset specific network control architectures, and NCS-3, and -4 both presume re-use of the evolved asset specific PoD network control architectures. The modeling team, and the SMEs, developed the set of PoD models. The model for the EBRE version is much more comprehensive, in part because there was more documentation at the architectural level and in part because it forms such an important part of the forward planning for the system evolution in all of the options. The PoD models for the DSE and NEE are less detailed, but these are presently operational and much better understood than the EBRE version that is still being designed.

It was critical to adopt common terminology during the course of the trade studies. While many terms are different than those used in the present three networks, but they are used here, in the PoD discussion, to make comparisons among the network elements clearer. Some of these terms are used to associate functional capabilities with physical system entities. There are three types of physical system entities for the integrated network, i.e., the ground station site (GSS), the Network Operations Node (NON), and the Integrated Network Operations Center (INOC). Other terms, for common functions, data objects, operations and interfaces have also been defined.

1. EBRE PoD Architecture

The EBRE PoD system architecture has several key elements and all of them were modeled at a common level of detail, derived from pre-PDR level presentations and documentation as source materials. All of these elements were essential to an understanding of how the NCS parts of the system were to function; they were either parts of the control system, or parts of the system under control, or were in a supporting role to schedule execution.

At a high level the EBRE system contains the following elements as shown in Figure 2:

- Space Ground Link (SGL) - includes high power amplifiers, low-noise amplifiers (LNA), and frequency converters; User Services Gateway (USG) - includes SLE, CSTS and user data interfaces; Digital Signal Processor (DSP), Service Management (SM) – includes planning, scheduling, and schedule execution; Fleet Ground Management (FGM) – includes TDRS Telemetry, Tracking and Command (TT&C) operations and ground equipment monitor and control; Enterprise Infrastructure (EI) – includes hardware, network, storage, and display platform.
- The new EBRE architecture uses a number of modern concepts, including a pool of shared, programmable servers (including blades servers and FPGAs), several high speed networks (10GigE), and a message bus based enterprise infrastructure.
- Network control is primary at one site, with a nearby backup site and executable schedules good for several hours of operation are distributed to the GSS and periodically updated.
- Planning and scheduling is centralized at the White Sands Complex (WSC)..
- Service Management (SM) orchestrates the schedule execution and the delivery of user services. It provides the users with service management interfaces.
- The Fleet Ground Management (FGM) element manages and controls the TDRS Fleet, and manages the Ground Segment hardware.
- SGL, DSP and USG all have local Control Test and Monitor functions that accept service requests and provide service status on the control plane. The CTM also functions load software and configurations, report detected faults, and provide performance information.
- The EBRE model has 2+ levels below that shown in Figure 2.

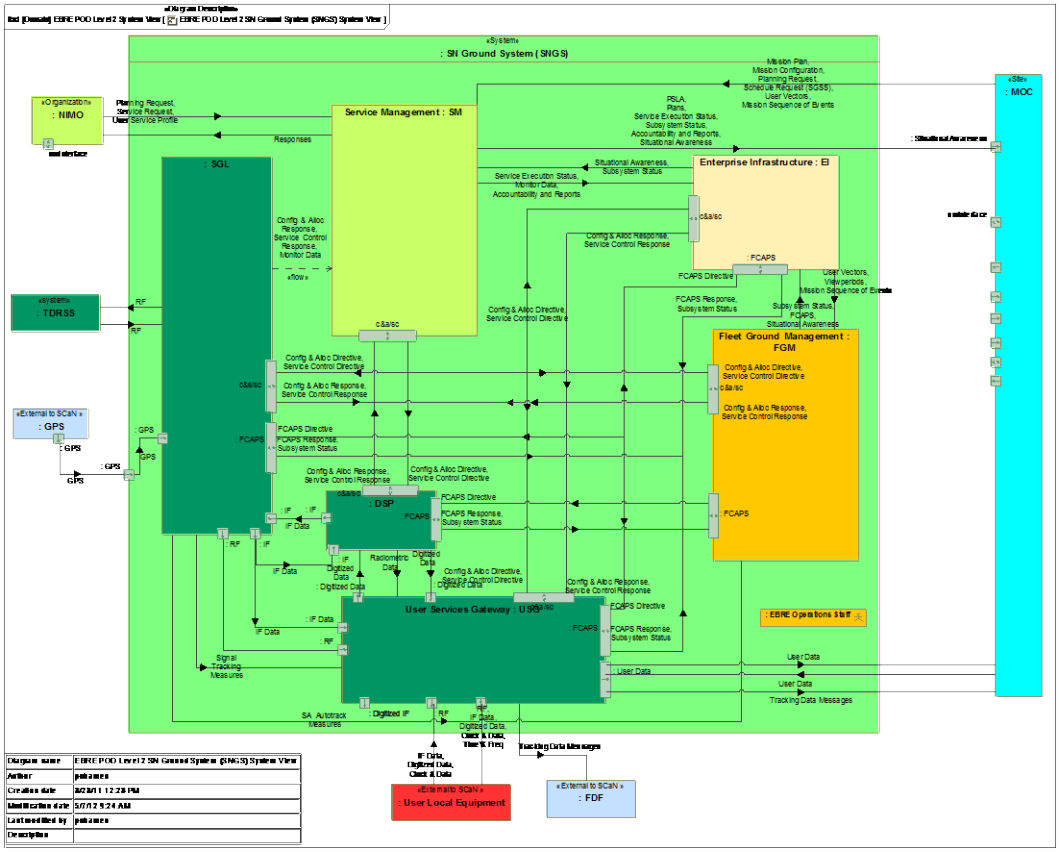

Figure 2. EBRE PoD Level 2 Software Architecture

The EBRE deployment model has two primary sites that act as Network Operations Nodes (NON) that may each do network control. There are Ground Station Sites (GSS) collocated with the NONs and two other Ground Station Sites (GSS) that have antennas and run schedule execution, and do signal processing and data delivery. The two sites with NONs also have GSS signal processing installations. This is similar to the existing SN deployment architecture that has been previously described elsewhere [7].

2. DSE PoD Architecture

For purposes of this study the DSE PoD system architecture is modeled as having three major elements, as shown in Figure 3. In the DSE architecture many more subsystems are identified, but in the following list only the ones most relevant for this study as shown:

- Service Preparation Subsystem (SPS) - includes the portal, planning, scheduling (SSS), predicts generation and asset management)
- Network Monitor and Control (NMC) – includes the link builder, link control, execution automation, monitor data, operator interfaces)
- Globally assigned and link assigned subsystems e.g. Antenna and Microwave (AMW), uplink, downlink, and related equipment
- Service Quality Assessment subsystem (SQA) providing accountability, reporting, situational awareness
- The DSE architecture uses a pool of equipment at each NON that is allocated as needed to a specific user link, along with equipment that is locally connected to each antenna e.g. LNA, transmitter, antenna control.
- Network control is distributed, with local operations staff at each NON/GSS and a central monitor and control function that coordinates among the NONs as needed.
- Planning and scheduling services are provided centrally at JPL, with distributed, collaborative user interaction.
- at JPL.
- The DSE model has 1+ levels below that shown in Figure 3.

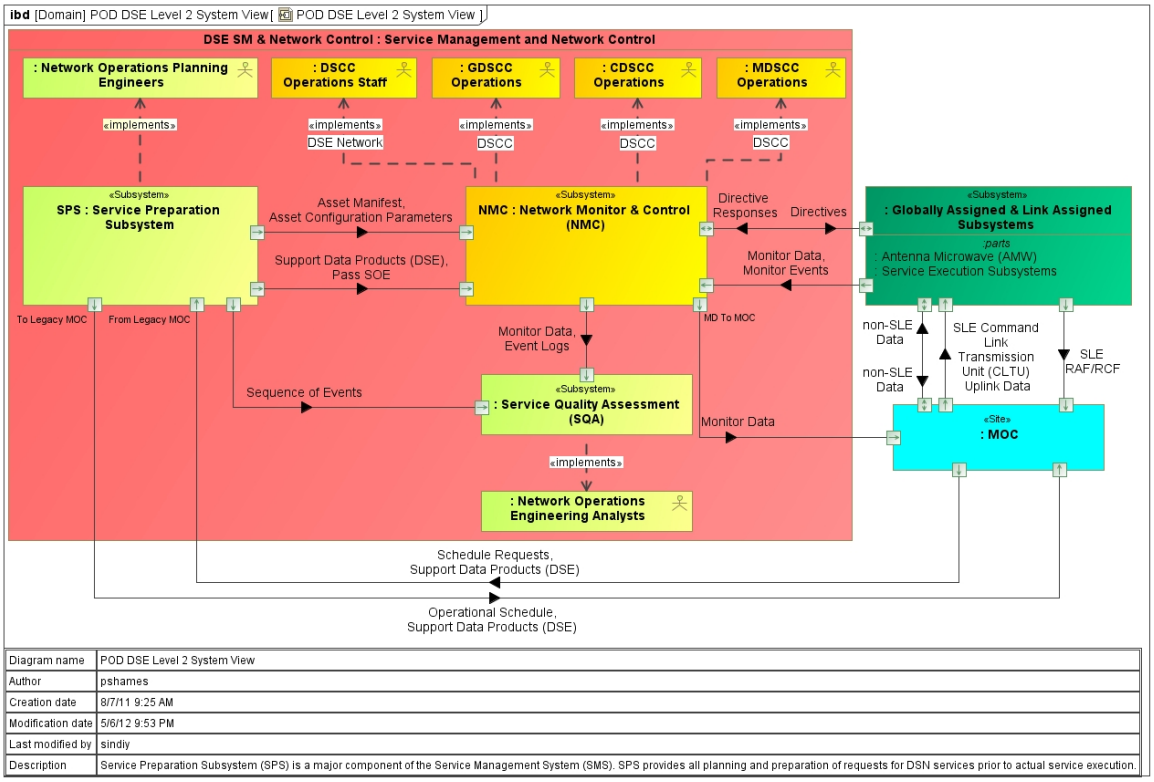

Figure 3. DSE PoD Level 2 Software Architecture

The DSE deployment model has three primary sites that act simultaneously as Network Operations Nodes (NON) and each has an associated Ground Station Site (GSS) with several antennas. Each NON runs schedule execution, and does signal processing and data delivery. The central JPL site at PoD will perform planning and scheduling functions, but is not expected to do any data handling other than routing of data to users in a hub and spokes physical network routing topology.

3. NEE PoD Architecture

The NEE PoD system architecture is modeled as having three major elements, as shown in Figure 4:

- Wallops Orbital Tracking Information System (WOTIS) is the planning and scheduling system, co-located at WSC with the EBRE planners.
- Hardware Control - Dewitt HWCtrl™, automated schedule execution driven by the schedule and configuration codes
- Link assigned subsystems – e.g. Antenna and microwave, uplink, downlink, and related signal processing and data delivery equipment
- The NEE architecture uses equipment at each NON that is assigned to each antenna e.g. LNA, transmitter, antenna control.
- Network control is distributed, with local operations staff at each NON/GSS.
- NEE also makes use of commercial antennas that are contracted services.
- The NEE model is only at the level shown in Figure 4.

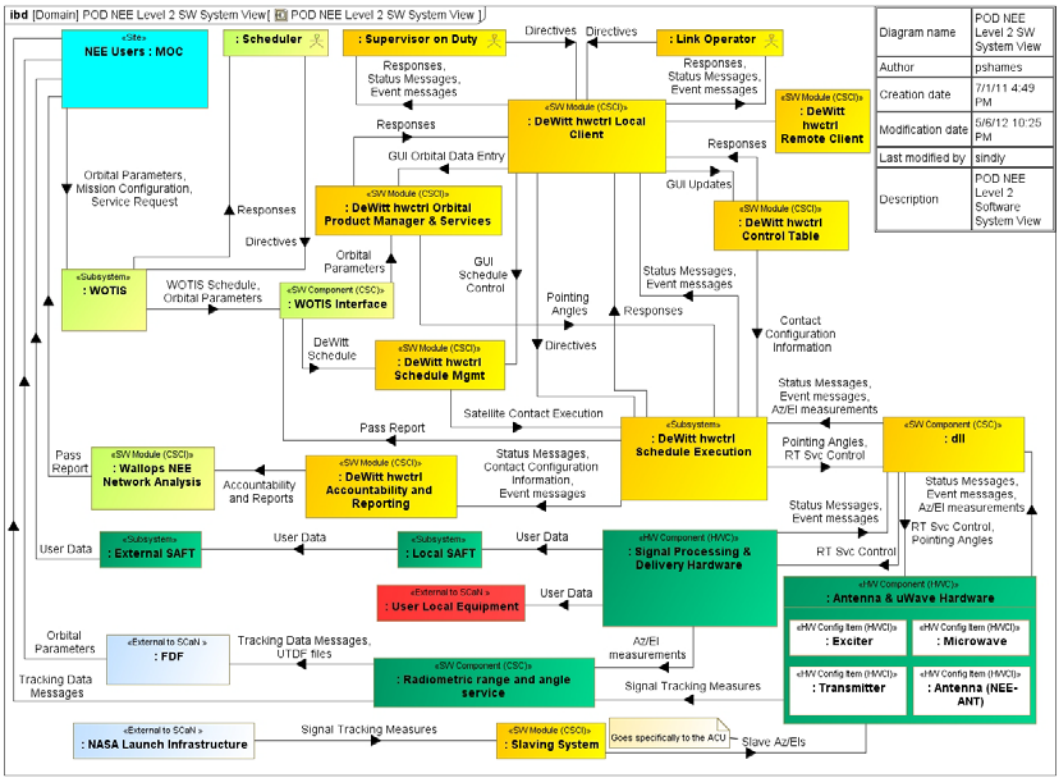

Figure 4. NEE PoD Level 2 Software Architecture

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The NEE deployment model has four primary Ground Station Sites (GSS) that each have one or more antennas and are controlled by a single Network Operations Node (NON). The NON drives schedule execution using a simple script and signal processing is done at each GSS. Most high-rate science data delivery is done directly to User Local Equipment (ULE) that is co-located at the GSS, with data returns arranged by the missions. Some data is returned to the users using simple port/socket interfaces or via the Standard Autonomous File Server (SAFS) located at each GSS and at GSFC. The WSC site at PoD performs planning and scheduling functions using the WOTIS software. The NON at WFF at PoD is not expected to do any data handling other than routing of data to users in a hub and spokes physical network routing topology.

IV. Trade Study Modeling Results

The NCS Trade Study resulted in the selection of the NCS-1 option that makes maximal use of the SGSS software being developed for the EBRE. The following salient features characterize the recommended SCaN Integrated Network Architecture:

- Common service execution capabilities deployed and operational at all Ground Station Sites (GSSs).
- Common network monitor and control capabilities deployed and operational at all Ground Station Sites (GSSs) and at the NONs that control them.
- An INOC or Service Portal providing a single access point for service planning, service requests, service accountability reporting, service dispatching, and network monitor & control interfaces with the user missions

In addition, the study team recommended that the following path be taken:

- Proceed with an NCS-1 prototype to evaluate functionality and viability of SGSS-provided Schedule Execution, FGM, and CTM implementations for meeting DSE & NEE requirements.
- If NCS-1 is deemed too hard to achieve due to cost and/or other circumstances, fallback to NCS-3, asset specific network control systems, retain common ISE, service management, & user missions interfaces.

The following subsections are intended to serve two purposes; 1) to introduce, at each level, views of the NCS-1 trade study option that was selected; 2) to describe how the model was constructed at each level so that the method we used is also described. Section V will provide some additional notes on the method.

In addition to the PoD models like the ones shown in Sec III, a number of other model artifacts and products were produced. The NCS Trade Study required models for each of the four options, NCS-1 thru NCS-4, and each option set included an overview of the whole system, network element deployment views and 3 levels of system details.

Each option included at least the following:

1. Level 1 Integrated Overview
2. Level 2 Deployment Model
3. Level 2 Network Element (system) models
4. Level 3 Subsystem Models
5. Level 3 Component Specializations

To enable easy and accurate development of these option specific models a library of model elements, subsystem specialization models, and models of the data objects and data structures composed from them was created. These libraries of elements and data objects were essential to supporting the composability of the different options, i.e. one from column “A”, one from column “B”, and also for ensuring consistent use of components and data across all the models. This approach has also proven extremely useful as a source of re-usable elements as we have moved into successive cycles of trade studies.

A. Level 1 Integrated Overview

The Level 1 integrated overview provides a high level view of how the system of systems is assembled from any central element, such as an Integrated Network Operations Center (INOC) and the re-engineered versions of the three network elements.

Figure 5 shows the NCS-1 functional element decomposition of the SCaN integrated network control hierarchy at a very high level. It shows the INOC for the INA that does planning and scheduling and connects to all three network elements using what is described as an INOC Protocol Interface, common to all three network elements. Only those SM system elements at each NON that do network control and directly connect using this protocol interface are shown on this view. The relevant EBRE system element is Service Management, and it is modified to include this new protocol interface and also to offer the new services defined for the INA. In this option each of the DSE and NEE also use a modified version of the EBRE INA SM system element to do network control at the NON, and these are specialized for those network elements and their particular services and user support requirements. This is similar to, but different from, the approach used in the EBRE PoD, and new services and interfaces will be added throughout the INA to meet future requirements.

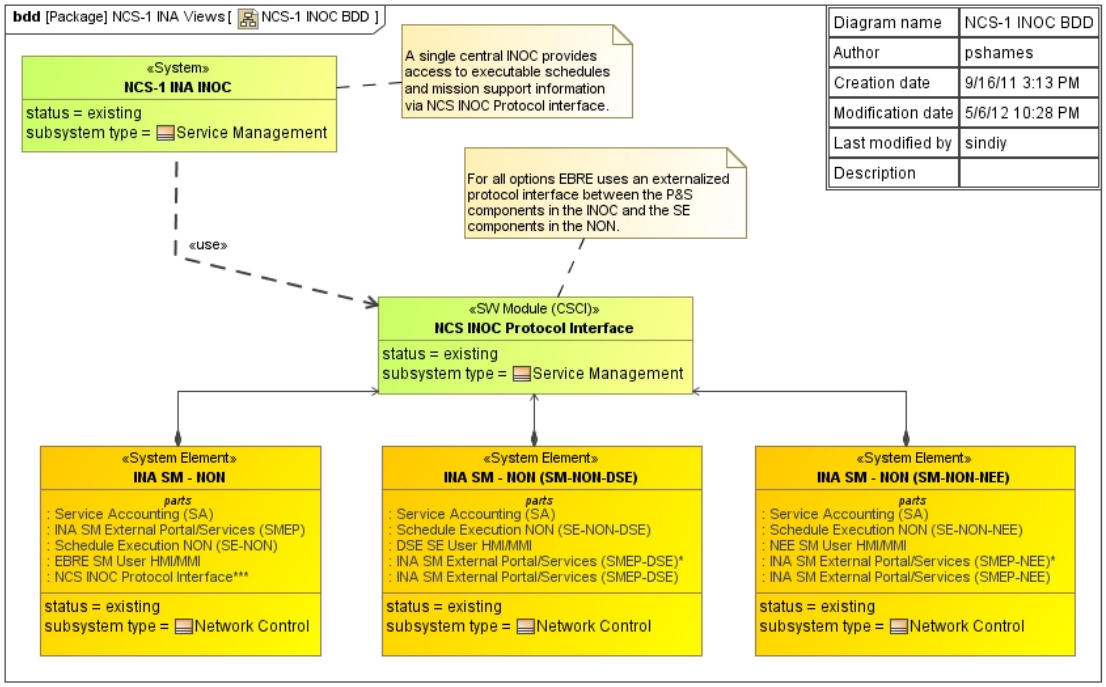

Figure 5. NCS-1 Level 1 Integrated Overview

B. Level 2 Deployment Model

The next kind of model developed is the Level 2 deployment model for each of the network elements. The deployment model is intended to describe the physical sites that perform the planning, scheduling, network control, and service execution functions allocated to them.

Figure 6 shows the NCS-1 version of the DSE, showing the three DSE ground station sites, each of which include the NON functions (network control) and the GT functions (service execution and also local control). The relationship between the INOC, assumed to be a single central site, and the distributed GSS is also shown. In this option, for DSE, the assumption is that the network element is using a "follow the Sun" approach, where each of the NONs only has operations staff during the prime (daytime) shift for that site, and the control of the entire network element is handed-off from NON to NON during the course of the day. The central NON, shown at JPL, only does coordination across the three GSS, performs high level monitoring and provides situational awareness of the whole network element. It has no direct control over schedule execution.

In Figure 6, the INOC, NON and GT each have a minimum level of internal structure shown, i.e. a *parts* list. Each NON has the same internal functional structure, though it is only shown for one instance. The instances shown here are the EBRE developed system elements that are used commonly across the NCS-1. These elements are specialized, as needed, for the DSE and NEE and to add new services and interfaces. Similarly, each GT has the same internal functional structure and includes the same sorts of network element specific specializations. There are similar deployment models for all of the three network elements for each of the four NCS options.

The internal structure of the parts shown in this diagram, and their derivation, is documented separately in lower level diagrams. The NON includes the network control parts of the SM element and the central parts of the FM element. The GTs each also have local network control derived from SM , the local FGM functions, and the adapted service execution functions derived from the SGL, DSP and USG.

Other physical deployment views are also possible. One example might be a view that shows the actual numbers of ground stations that are available at each GSS. Another example might be to show the physical connectivity among the GS, GSS, NON, INOC, and the users. These would use a different style of SysML™ diagram, such as an IBD, instead of the compositional BDD used for these deployment views.

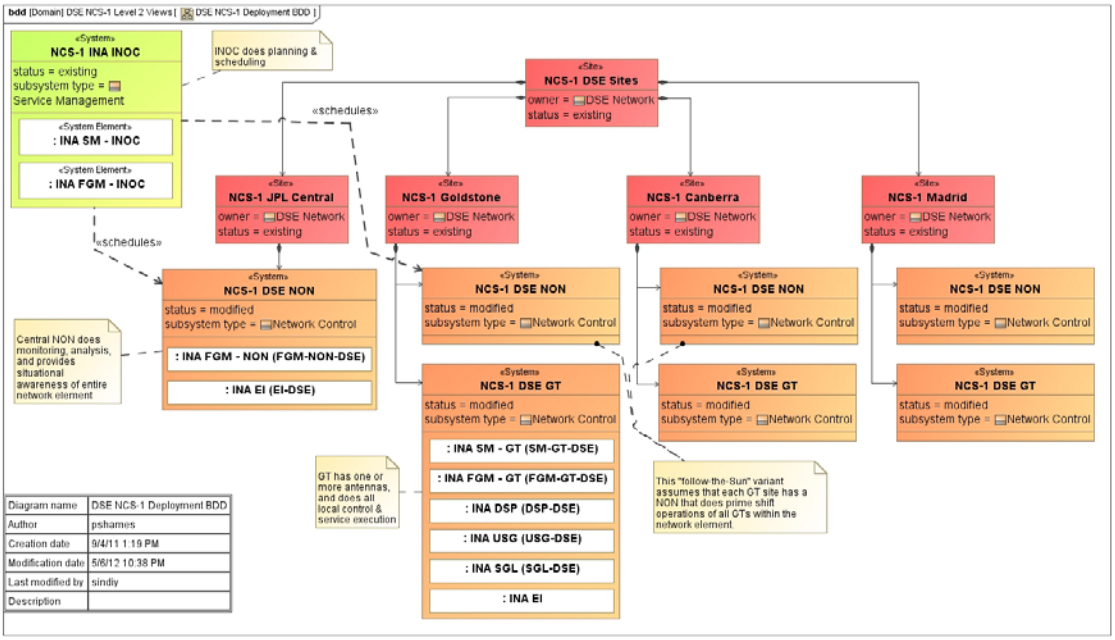

Figure 6. NCS-1 DSE Level 2 Deployment Model

C. Level 2 Network Element System Model

Figure 2 showed a Level 2 view of the EBRE software architecture, representing all of the major elements of that software system, the high level control and data flows, and interactions with key elements that are outside the system and interface with it. Often it is necessary to depict all of the functional elements in the system and how they are composed. For this a different usage of a SysML™ BDD is used to show software composition.

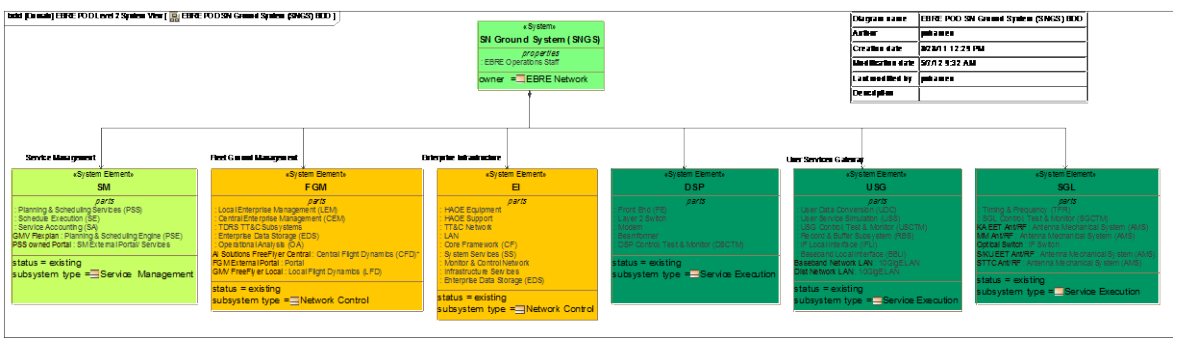

Figure 7. NCS-1 EBRE Level 2 System Composition Model

The Level 2 system model in Figure 7 shows the composition of the EBRE software system, its system elements, and also the next level de-composition of those elements down to subsystems. There are comparable model views for the DSE and NEE as well. Successive diagrams in this same functional BDD composition style have been developed as needed to decompose the subsystems to lower level objects.

Other Level 2 and 3 IBD diagrams, not shown here, provide representations of control and data flows within and among the system elements. These diagrams look like Figure 2 in style, but are at the System Element level (Level 3 in the model) and show the internal interfaces among the system modules in each element and the flows into and out of each system element from other modules external to the system element.

Level 3 Sub-System Model

In order to understand in sufficient detail how the INA Network Control Software is to operate a series of Level 3 sub-system models were developed. Network control essentially touches on all of the lower level subsystems that must be controlled in order to produce services. This study assumed that there was a planning and scheduling

function in the INOC that produced an executable schedule and that a common set of service execution equipment was used to actually perform the services.

In Figure 8 the Level 2 network control elements allocated to the NEE NON are decomposed down to Level 3 network control functions . These are derived from the SM network control and FGM central parts, and also include EI support elements. There are similar views for the DSE and EBRE in the model. This particular view also uses a BDD compositional style, but other views (not provided here) show control and data flows in an IBD style. There are three things of note here:

1. The decomposition of the Level 3 elements described in Figure 7 is taken down to the next level of detail in Figure 8.
2. Only those system elements deployed at a NON are shown. This is a further elaboration of the deployment diagram in Figure 6. There is a comparable GT diagram as well.
3. The color-coding is used to indicate the components that require change (orange instead of golden yellow) in order to adapt the EBRE developed elements for use in the NEE context. Many of these next level software modules are themselves described on specialization diagrams that provide more detail on the magnitude of the required changes.

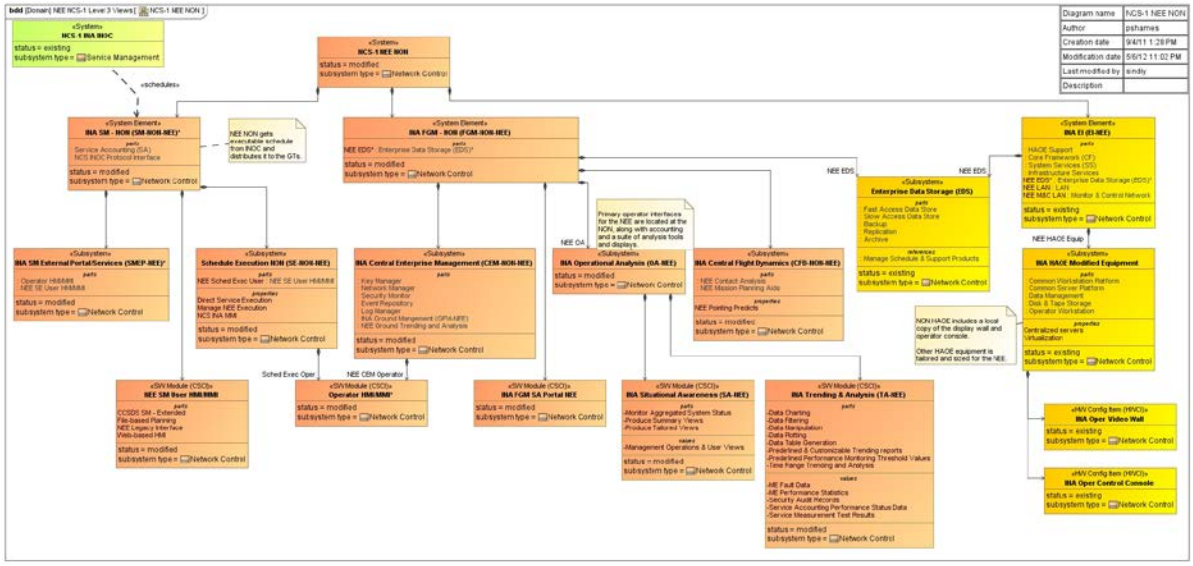

Figure 8. NCS-1 NEE Level 3 NON Network Control Composition Model

D. Component Specializations

From a modeling perspective, one of the key aspects of this trade space model was to capture just what was re-used, what was modified, what the extent of those modifications were, and how these modified elements would be combined to create the various trade space option configurations.

The element libraries, described in Sec III.C were a key part of managing this part of the process. Each of the system elements, the subsystems that compose them, the SW modules that compose them, and any lower level decompositions were created in the Element Library part of the model. An example of this, showing the various elements modeled for the INA and the PoD is shown in Figure 9. In reality the model was developed from the bottom up, by creating elements that were then composed to make higher level elements. This is exactly the reverse of the description in this paper that starts at the top and then shows how the model is decomposed to lower layers. This top-down presentation of system composition is a very familiar way to explain system architectures, but the model is best constructed from the bottom up so that "atomic" building blocks may be used to compose higher-level components.

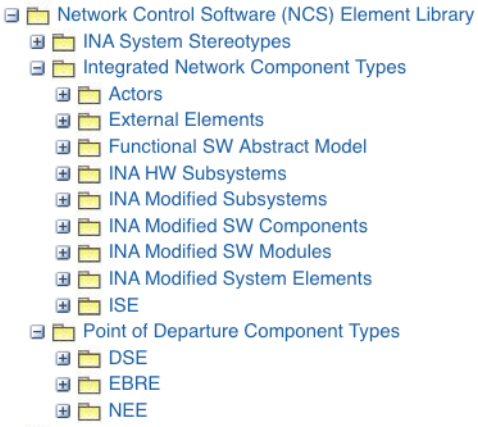

Figure 9. Element Library Model Structures

Figure 10 shows an example of a specialization diagram for the Service Management system element, which is the key element in the network control part of the system. It was essential to be able to describe just which parts of this system element were to be allocated to the INOC, the NON, and the GT. Further, it was essential to understand which parts of this system element needed to be modified in order to accommodate the different needs of the DSE and NEE .

The yellow/green component at the top is the original EBRE SM element. The left yellow/green component is the subset of SM functions that are to reside at the INOC. The central group of golden elements are those sub-sets of the SM functions that are to be deployed at the DSE and NEE NONs (along with the NCS-2 specializations) and the right hand group is the sub-set to be deployed at the DSE and NEE GTs. All of the variants for this SM system element are shown on one diagram, making it easier to understand the changes from one use to another. Similar specialization BDDs were produced in the Element Library for all of the components that needed to be decomposed or re-engineered in some way. These modified components were then used to compose the option models.

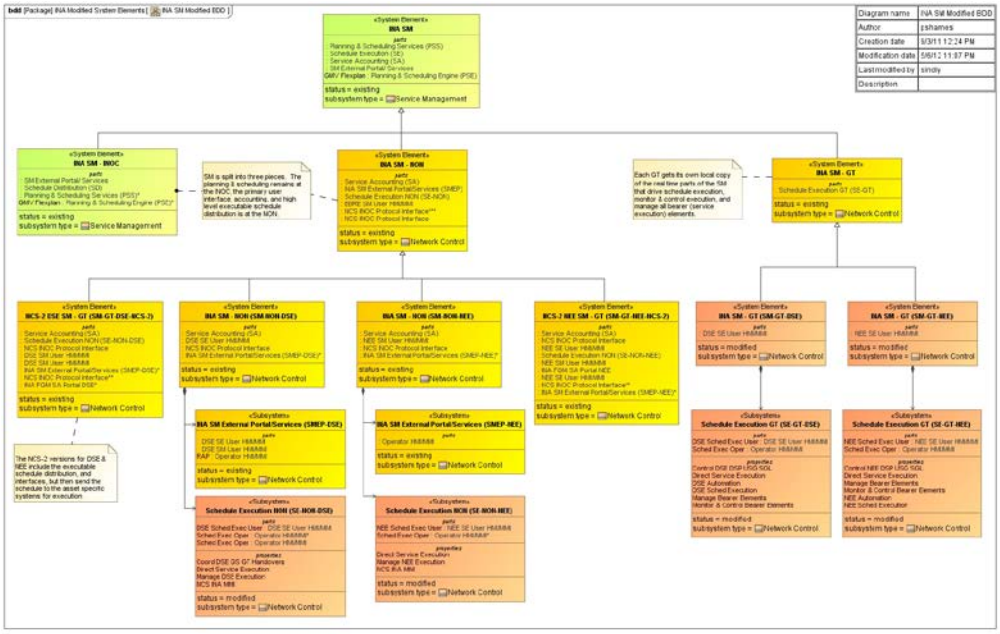

Figure 10. Service Management (SM) Specialization

V. Some Thoughts About Trade Study Modeling

A. Summary of the Modeling Approach

The previous sections have described the approach used for this particular trade study using examples, along with some of the sorts of products and results that were produced. This section provides some guidance on how to apply a generalization of this method to other trade studies.

The fundamental steps are:

1) Define the problem space and scope, per stakeholder concerns
2) Clarify the set of designs and artifacts for be produced at a high level
3) Define the overall modeling framework approach to be used
4) Identify the kinds of design artifacts needed to answer the questions being posed by the key stakeholders
5) Select the set of viewpoints to be used – e.g. functional, physical, logical, information, organizational, deployment, etc, and the set of views to be produced
6) Define the trade space and element library model hierarchy and at least the top two levels of decomposition of the hierarchy
7) Develop any necessary stereotypes, element types, color codes to mark model elements and for visual indication of element properties
8) Define the major types of elements to be used in the views and create the necessary libraries of composable objects
9) Define and refine the major elements that will be used to produce the trade space models
10) Compose the trade space models
11) Analyze the trade space models
12) Do not be afraid to go back to earlier steps, even step 2 or 3, and refine the framework and the models until they are adequate to the task

All of these steps were utilized in this trade study effort, including the last. To paraphrase Frederick L. Brooks "Models are like waffles. Be prepared to throw the first one away." Or, as George Edward Pelham Box stated, architects and modelers should remember that "all models are wrong, but some are useful."

B. Observations on Trade Space Modeling

The initial impulse to adopt a formal modeling approach has paid off, and it has provided significant added benefits in the Cycle 4-5 trade studies that are now in progress. The SysML™ methods can be very powerful and permit a lot of flexibility in how models can be constructed, if they are used resourcefully. This flexibility is both a blessing and a curse. As we have learned, casual uses of modeling methods may allow quick production of various artifacts (once the learning curve has been climbed), but these facile approaches do not necessarily lend themselves to easy re-use. Quickly produced diagrams do not necessarily produce a good model. Taking a more rigorous approach to developing the modeling framework takes more time, but better supports model composition, development of complex trade spaces, and re-use and refinement of model elements.

There is an important distinction to be understood between the SysML™ models that were developed for this study and the Cycle 1 presentation style "architecture models" developed in PowerPoint™, Visio™, or other drawing tools. On the surface both provide graphical views of the system being modeled and any of these tools can quickly produce drawings that represent systems elements, but these are just drawings. The boxes, lines, and connections have no intrinsic meaning in the tool. In SysML™, however, the tool is actually producing a complex, multi-level, model, where each of the elements is formally defined, and where associated properties, composition, connections, and even behavior may be clearly articulated. The real benefits are in the model; the drawings are just convenient representations or views of the model to aid understanding.

The processes of system architecture modeling, and the tools that support it, have a significant learning curve. Training in SysML™ and a modeling tool that implements it, of at least a few days duration, is a great help in getting started with the methods. Even with that there is a lot of "on the job training" that is required. At JPL we are fortunate to have a growing cadre of experienced and beginning modelers, the Modeling Early Adopters (MEA) that forms a support community. JPL has also invested institutionally in tools and some modeling infrastructure called Integrated Model Centered Engineering (IMCE)[8,9]. All of these provide a lot of support and a knowledge base to draw upon.

Formal models take some getting used to, for those who develop them and for those who are asked to review them. We developed some simple guides and tutorial material, and used "Start Here" landing pages, overview pages, copies of the simple PPT graphics (using Content Diagrams), and hyper-linked icons within the model, and these have enabled easier model navigation. A tutorial "Guide for the Perplexed" was also developed to gently guide reviewers through the HTML browser-readable version of the model that was periodically made available.

In getting started with any architecture models, whether of single system designs or complicated, multi-dimensional trade space modeling, attention to viewpoints and views is essential to produce readable and useful models. This effort drew on the set of viewpoint specifications described in the RASDS, but other sets of viewpoints and views may be useful for different modeling efforts. Operational activity models, in particular, may benefit from some of the DoDAF views. Arriving at a common understanding of the INA terminology was also important, and there is a set of information views in the model. To help the team grasp all of the concepts and their relationships a Mind Map was also produced and then translated into the formal model in SysML.

While developing models for single systems is becoming a common practice, doing the sorts of trade space and System of Systems modeling that was required for this task appears to be less well understood. There is little support for it or literature on how to implement it and very few worked examples have been published. It requires a different approach to modeling than monolith system models, and we are still learning how to do it. There is a challenge in finding an effective way to structure the model to effectively create the trade space models, and there is a challenge in identifying the right depth to drill down so that the model adequately discriminates among the options. What is clear is that these models appear to have a real value in helping distributed architecting and modeling teams document and understand complex system interactions and to explore a multi-dimensional trade space. It appears that these models, while they are complex, can be used with some success to communicate the technical details of a complex trade space effectively, even to stakeholders untutored in modeling, if sufficient care is taken to explain the modeling concepts and to produce technically correct and visually accessible model that resonates for the users..

An area where more work can be done is in developing more comprehensive metrics from the model itself. We did some experiments in applying the Operational Query, View Transform (QVTO) language[10] to the models. QTVO scripts can assist in model analysis and developing size and complexity metrics, even if the model is not fully formed. We applied QVTO and developed some completeness and connectivity measures, and also identified some initial assessments of complexity that allowed inter-option comparisons. However, one of the things that hampered full utilization of this capability was the fact that the PoD models for DSE and NEE were at a different level of decomposition detail than those developed for EBRE. As a result, quantitative comparisons across the NCS-2, -3 and -4 options that included large segments of the PoD DSE and NEE could not with certainty be compared with those that were more derivative of the EBRE systems. This could have been rectified, given time, but since modeling, analysis, costing and scoring work that was done allowed NCS-1 to be selected (subject to verification through prototyping) the added investment was not made.

Doing this type of MBSE trade study with a distributed team brings an added level of complexity. Even with frequent use of teleconferences, email, and periodic face-to-face meetings this sort of effort is tough to organize. What helped a lot was partitioning the problem into systems and software parts and operational parts and allocating responsibility along these obvious lines. This worked quite well once some of the fundamental differences in how the involved organizations worked had been resolved. An early lesson was the need to adopt a single common modeling approach. As noted earlier, one group had experience with DoDAF, the other with SysML™. We tried a hybrid approach at first, but this proved un-workable because of limitations in the ability of UPDM to deal with the SoS trade space and also the model depth that was needed. It is not clear if this is a limitation in DoDAF itself or in the MagicDraw™ implementation of the UPDM profile. Even though the study was done completely within NASA, across NASA centers, we also discovered that institutional security policies may make shared modeling complicated, requiring firewalls to be traversed, using full tunnel VPNs and needing special user credentials. Due to these remote access constraints, working on the models while on travel became an even more challenging problem for several of us.

VI. Conclusions

SCaN has a very challenging problem in trying to integrate three quite diverse networks that have operated as independent entities for decades. There are technical, operational, functional, cultural and political issues to be resolved. The adopted method of doing several cycles of trade studies, accompanied with the concomitant pruning of the trade space, has allowed the technical parts of the problem to be worked while also providing the organizations with an opportunity to come to terms with the proposed changes. The modeling methods described

here have become an important part of analyzing the technical options and of driving the analysis of alternatives and the costing of the resulting designs. While the designs are hardly at a level where they can be implemented they are at a sufficient level of detail to permit the salient features to be discriminated and to permit comparative cost analyses.

Developing these complicated trade space models has been a learning exercise. There is little in the published literature describing how to approach this sort of modeling effort. But is it clear that there is a significant benefit, both to the technical team doing the studies and to the reviewers of the resulting design and analysis materials, in having clearly articulated models of these systems and of the possible options. And as the next cycles have proceeded it is also clear that using modeling tools, with all the possibility of consistency checking, successive refinement, composability, and re-use has brought significant advantages.

Appendix A
Acronym List

AMW	Antenna Microwave
AoA	Analysis of Alternatives
BDD	Block Definition Diagram
CCSDS	Consultative Committee for Space Data Systems
COOP	Continuity of Operations
CSTS	Cross Support Transfer Service
CTM	Control, Test, and Monitor
DoDAF	Department of Defense Architecture Framework
DSE	Deep Space Element
DSN	Deep Space network
DSP	Digital Signal Processor
EBRE	Earth Based Relay Element
EI	Enterprise Infrastructure
FGM	Fleet Ground Management
FPGA	Field Programmable Gate Array
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
GSS	Ground Station Site
GW	Gateway
HW	Hardware
I/F	Interface
IBD	Internal Block Diagram
IMCE	Integrated Model Centric Engineering
INA	Integrated Network Architecture
INOC	Integrated Network Operation Center
ISE	Integrated Service Execution
JPL	Jet Propulsion Laboratory
LNA	Low Noise Amplifier
MBSE	Model-Based System Engineering
MEA	Modeling Early Adopters
MOC	Mission Operation Center
MODAF	Ministry of Defence Architecture Framework (British)
NASA	National Aeronautics and Space Administration
NCS	Network Control Software
NEE	Near Earth Element
NEN	Near Earth Network
NMC	Network Monitor and Control
NON	Network Operations Node
PoD	Point of Departure
QVTO	Query, View, Transform, Operational
RASDS	Reference Architecture for Space Data Systems
SAFS	Standard Autonomous File System
SCaN	Space Communication and Navigation
SDR	Software Defined Radio
SGL	Space Ground Link
SGSS	SN Ground Segment Sustainment
SLE	Space Link Extension
SM	Service Management
SME	Subject Matter Expert

SN	Space Network
SoS	System-of-Systems
SPS	Service Planning Subsystem
SSS	Service Scheduling Subsystem
SW	Software
SysML™	Systems Modeling Language
TDRS	Tracking and Data Relay Satellite
ULE	User Local Equipment
UML	Unified Modeling Language
UPDM	Unified Profile for DoDAF/MODAF
USG	User Service Gateway
WFF	Wallops Flight Facility
WOTIS	Wallops Orbital Tracking Information System
WSC	White Sands Complex

Appendix B
Glossary

Cross Support Transfer Service (CSTS)	The CSTS standards define a generic framework for defining and implementing future SLE-style Transfer Services. The toolkit will be a single recommendation specifying the common aspects of SLE Services, with Service Specific recommendations being defined as deltas to the common recommendation.
Ground Station (GS)	A ground-based station or terminal that performs space communications.
Ground Station Site (GSS)	A collection of one or more ground-based stations or terminals that performs some Service Execution functions local to the communication assets it is affiliated with, and some Network Control functions local to communication assets it is affiliated with.
Integrated Network Architecture (INA)	A unified space communications and navigation network infrastructure capable of meeting both robotic and human exploration mission needs.
Integrated Network Operations Center (INOC)	A centrally located operations center that performs some Network Control and/or Service Management functions for the entire Integrated Network, plus, in some options, some Service Execution functions.
Network Control functions	The INA functions for Network Scheduling, Network Asset Configuration & Control, Network Asset Monitoring, and Space Internetworking Management.
Network Control Software (NCS)	The INA software systems that perform network control functions.
Network Operations Node (NON)	An operation control center that performs some Network Control and/or Service Management functions dedicated to a network element (i.e., EBRE, NEE, or DSE).
Service Execution functions	The INA functions for Forward Data Delivery, Return Data Delivery, Radiometric Data Delivery, and Position & Timing.
Service Management functions	The INA functions for Service Planning, Service Request Scheduling, and Service Accountability Reporting.
Space Link Extension (SLE)	The SLE standards define a range of services that are required to configure, operate, and supervise the ground data systems used for space communications. They apply to data systems that are able 1) to receive CCSDS Space Link data structures from a spacecraft, or 2) to send CCSDS Space Link data structures to a spacecraft, or 3) to transfer such CCSDS Space Link data structures between ground-based entities.
System Modeling Language (SysML™)	The OMG systems Modeling Language **(OMG SysML™)** is a general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities.

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