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Functional Resources – Model Driven Standardization for Monitoring and Control

Holger Dreihahn[a], Marcin Gnat[b], Dr Colin Haddow[c], Dr Todor Stoitsev[d]

[a] *ESA/ESOC Robert-Bosch Str.5, D-64293 Darmstadt, Germany,* mailto:holger.dreihahn@esa.int
[b] *Deutsches Zentrum für Luft- und Raumfahrt (DLR)Raumflugbetrieb und Astronautentraining,* mailto:marcin.gnat@dlr.de
[c] *Scotty Consulting UG, Germany,*mailto:Scotty.Consulting@scotty-enterprizes.com
[d] *SpaceCube GmbH, Germany,* mailto:t.stoitsev@space-cube.de

Abstract

In 2008, after a routine pass ESA lost contact to the XMM-NEWTON spacecraft. As described in [7], the standard recovery procedures couldn't resolve the problem and spacecraft emergency was declared. With the help of NASA's Deep Space Network and the more powerful 80 kW amplifier, the XMM-NEWTON could be commanded and finally recovered. It is worth to mention, that the setup of the short-term cross support of the Goldstone station for the XMM-NEWTON recovery revealed some difficulties to achieve a common understanding of the configuration and monitoring parameters. As one of the lessons learned, ESA created a so called 'Monitored Data Dictionary' with the goal to unambiguously define ground station configuration and monitoring parameters. The approach of the 'Monitored Data Dictionary' evolved under the lead of the CCSDS Cross Support Transfer Services Area into the concept of Functional Resources, which are registered at the Space Assigned Number Authority (SANA) [1]. Today the Functional Resource Registry covers the core functions of a typical ground station for radio frequency (RF) communication. Examples of Functional Resources include the Antenna, modulator, demodulator and many more.

Conceptually, Functional Resources aim at standardizing monitoring parameters, control directives and events for functions provided by ground stations in terms of semantics, identifier, and type. Besides problems like the rather dramatic one of the XMM-NETWON described above, this is an important aspect addressing real-world operations and integration problems. Many organizations and equipment vendors define monitoring parameters, events and directives, in similar yet different ways, which increases integration costs for physical equipment of owned ground stations and external stations augmenting owned ground stations. In addition, the operational robustness and efficiency is potentially enhanced, as misunderstandings can and do occur when interpreting private definitions. Functional Resources define the monitoring parameters which can be transferred from a ground station to a user, typically a mission operations center, by means of the CSTS Monitored Data Service [2].

CCSDS has taken a model-based approach to define the Functional Resources registered at the Space Assigned Number Authority (SANA) [1]. At the time of writing 27 Functional Resources with 290 parameters, representing the essential functions and parameters of a Radio Frequency (RF) ground stations are registered and available for use. To our knowledge this is, world-wide, the first set of standardized monitor parameters for ground stations.

To facilitate this, the CCSDS CSS Area has taken a model-based approach: From one source of information, the Functional Resource Model (FRM), we produce the XML data published at SANA, the ASN.1 [5] parameter definitions as used by the CSTS Monitored Data Service and finally documentation to facilitate the CCSDS internal review of Functional Resources. As described below, the model-based Functional Resource approach has even more potential to standardize and streamline ground station configuration and finally automated operations on an equipment independent level.

1. Acronyms/Abbreviations

ASN.1	Abstract Syntax Notation 1
BER	Basic Encoding Rules
CCSDS	Consultive Committee for Space Data Systems
CESG	CCSDS Engineering Steering Group
CFDP	CCSDS File Delivery Protocol
CLCW	Command Link Control Word
CSTS	Cross Support Transfer Service

EDS	Electronic Data Sheet
EMF	Eclipse Modelling Framework
FR	Functional Resource
FRI	Functional Resource Instance
FRIM	Functional Resource Instance Model
OID	Object Identifier
RF	Radio Frequency
PLOP	Physical Layer OPerations
SAP	Session Access Point
SANA	Space Assigned Number Authority
XDS	XML Schema Definition
XML	EXtensible Markup Language

2. Introduction to Functional Resources

Each Functional Resource is an abstraction of a function used within a ground station. As depicted in Figure 1, a Functional Resource has typically an input signal/data and outputs processed signal/data; the processing typically follows a CCSDS recommendation. One example is a CCSDS 401 ([3]) compliant demodulator*, which takes as an input the carrier signal from the antenna and outputs the demodulated symbol stream.

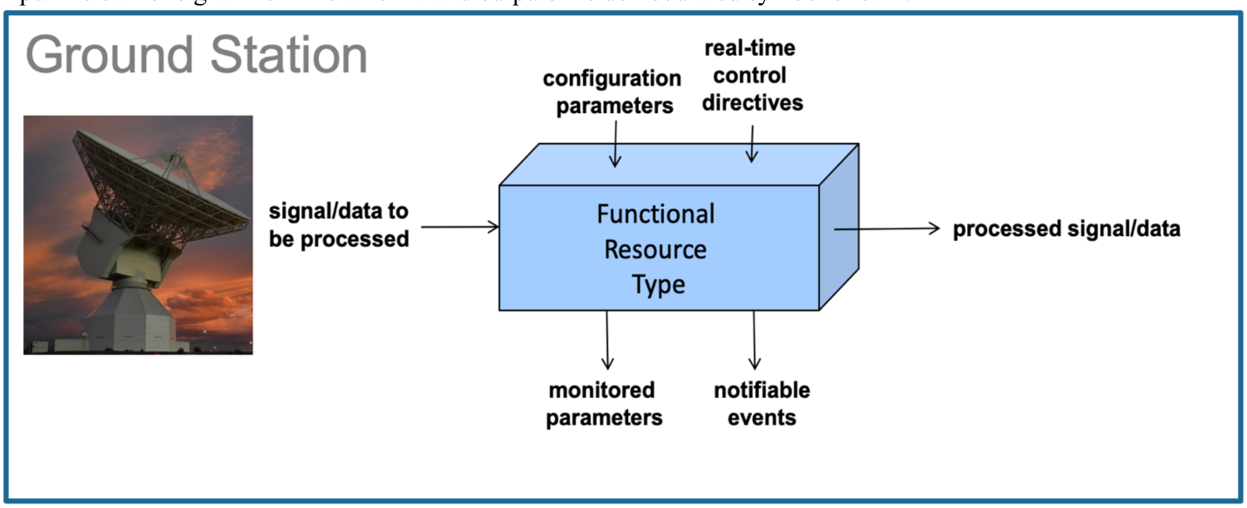

Figure 1 Functional Resource Type

The novelty of Functional Resources is the standardization and formal registration at SANA [1] for:

- Configuration Parameters
- Real Time Control Directives
- Monitored Parameters
- Notifiable Events

Each of the above has a unique identifier, a clear semantic definition, and an expressive formal type definition. Type definitions support on top of simple and enumerated types also complex types and constraints.

The final design goal of Functional Resources is to characterize parameters, events, and control directives on a functional, equipment independent level. Functional Resources are informative enough to provide operators with a precise, harmonized view of the current operations carried out by a ground station, and at the same time abstract enough to cater for the fact that different ground stations make use of different, heterogenous types of equipment. That concept is based on the observation that vendor specific equipment like antennas or modems often provide similar if not the same functions. They do of course differ in the way they are implemented, performance, level of integration and,

* Functional Resource Type Ccsds401SpaceLinkCarrierRcpt

finally, in how these functions are configured, monitored, and controlled. However, by nature the configuration and the monitoring parameters and to some extent control directives are again similar – and that is what Functional Resources aim to harmonize for the sake of a consistent way to configure, monitor, and control ground stations.

3. Functional Resource Modelling

When the CCSDS CSS Area started the authoring of functional resources, an excel spread sheet was used. That approach worked to capture names and semantic descriptions of Functional Resources. However, it became quickly clear, that especially the management of the Object Identifiers (OID) was not scaling. Maintaining consistency for hundreds of OIDs manually simply does not work. Inserting a new parameter 'in the middle' requires renumbering of preceding parameter OIDs - an error prone and tedious exercise.

The way out was the creation of a structured editor for Functional Resources, which allowed the implementation of an algorithm to automatically create and manage all required OIDs. The Functional Resource editor has been implemented with the Eclipse Modelling Framework (EMF, [4]), a model-based technology requiring very little low-level programming, the focus is on domain data modelling.

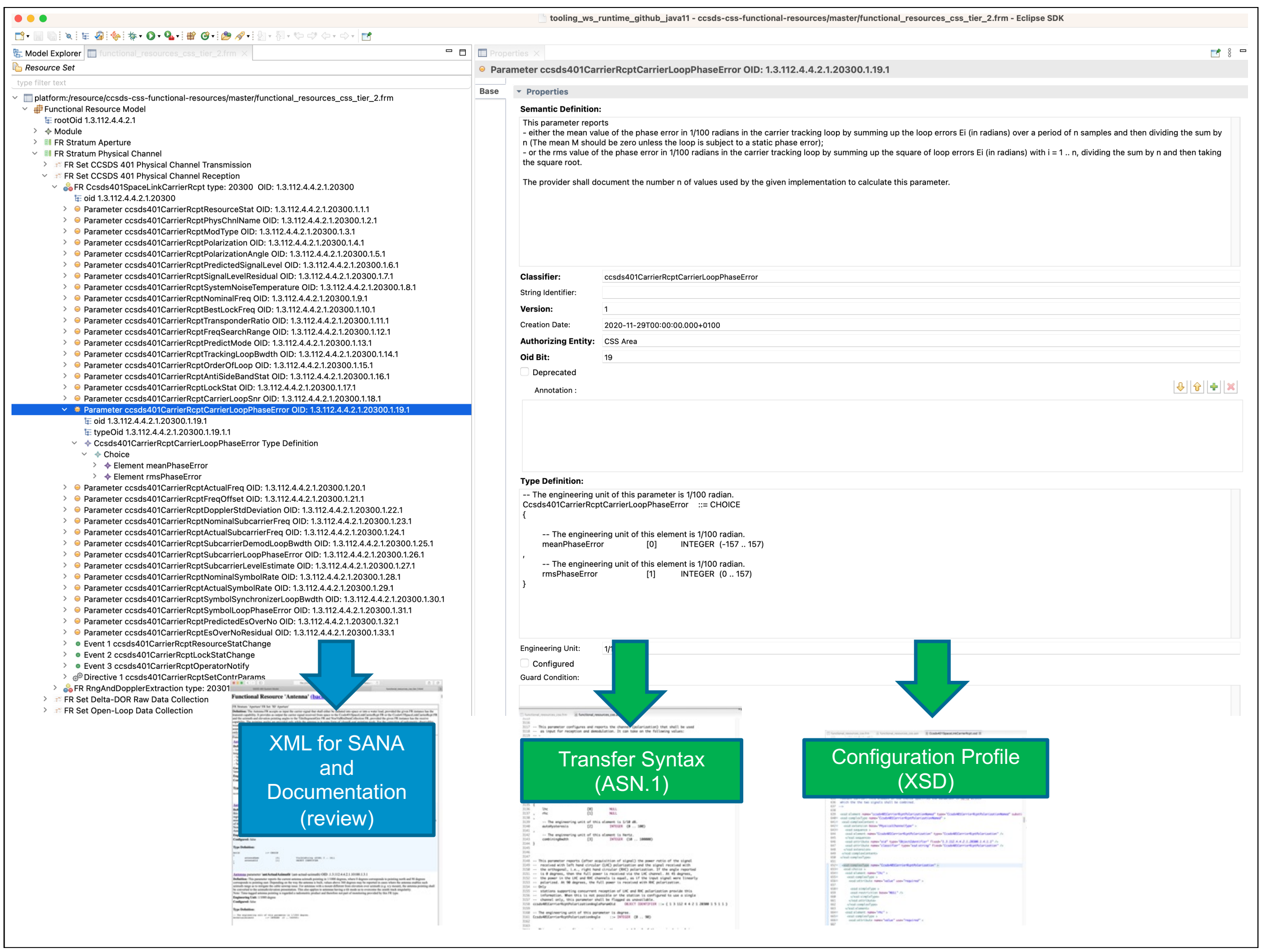

Figure 2 Functional Resource Model Editor

As shown in Figure 2, the Functional Resource Editor supports editing Functional Resources in a tree with property pages to enter textual descriptions. For the convenience of the user, all OIDs are generated automatically by the editor in a consistent manner. That fulfils the first and foremost goal to generate correct and consistent OIDs, finally registered at the Space Assigned Number Authority (SANA) in the Functional Resource Registry [1].

However, the use of a model-based approach allowed straightforward extension to support additional functionality:

- For review purposes the Functional Resources can be exported to word and HTML documents, which facilitate the CCSDS internal review process.

- The parameter type definitions and their associated OIDs can be exported to ASN.1, which allows CSTS Monitored Data Service implementations to use these consistent ASN.1 definitions for the delivery Functional Resource parameters.
- To support XML based configuration profiles, the configuration parameters as defined by the Functional Resource Model can exported to XML schemata (XSD).

The specification of Functional Resource relations are supported by a graphical representation as shown in Figure 3.

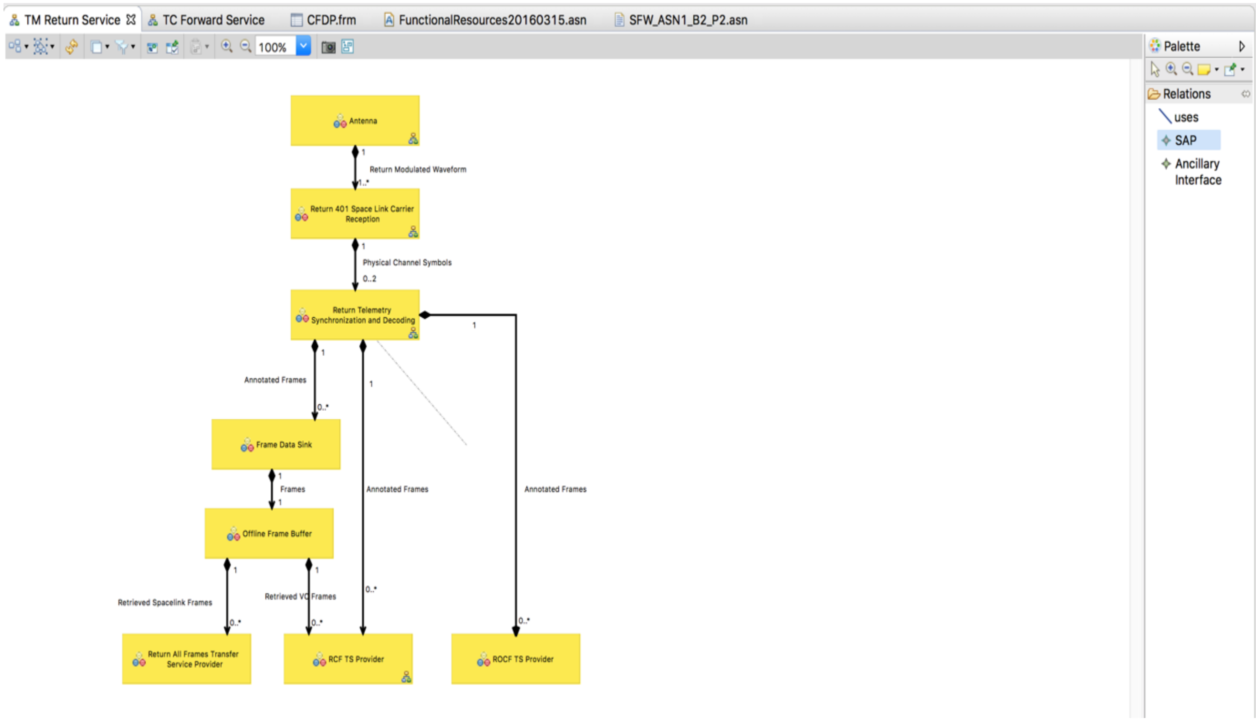

Figure 3 Graphical Functional Resource representation

There are two types of relations Functional Resources can have. So called Service Access Points (SAP) are used to express data flows between two Functional Resources, Ancillary Interfaces can be provided to other Functional Resources to ensure proper functioning. An example of an ancillary interface is the CLCW interface, which provides CLCW extracted from the telemetry to the forward link to regulate Physical Layer Operations (PLOP).

4. Model Transformations

The use of a model based Functional Resource editor, providing automatic OID generation and data in a formally defined and machine-readable way has boosted the productivity and quality of the Functional Resource standardization process substantially. Without such tooling, the efficient production and maintenance of the SANA Functional Registry in a consistent way would not have been possible.

However, a real-world implementation of the Functional Resource concept requires more than the SANA Functional Resource provides. It is suggested that in addition the following artefacts based on Functional resources are considered for implementation:

- *ASN.1 definitions* for CSTS Monitored Data service to provision Monitoring Data to users
- Monitoring and Control Model definitions to manage *Functional Resource Instances* at runtime
- Configuration Profiles of Functional Resources based on *XML schemata* for configuration purposes

Technically the above can be achieved or at least supported by model-to-model (M2M) or model-to-text (M2T) transformations. From a single source of truth, the Functional Resource Model, one can generate ASN.1 definitions (M2T), XML schemata (M2T) and a Functional Resource Instance meta model (M2M). As all derived products are generated from one single source, consistency is built into the approach. Labour-intensive interpretation and processing of documents is mostly eliminated, productivity and consistency is drastically improved. Clearly these gains do not come for free; the model transformations must be implemented, verified, and maintained. Moreover, it must be possible

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to propagate updates of the Functional Resource Model along the generated products. So far, the experience with the implemented transformations (ASN.1 and XSD) are positive. The benefits clearly outweigh the effort.

5. Use Case: Monitored Data Service

The CSTS Monitored Data Service [2] specifies the protocol to transfer monitored data and events from a provider, typically a ground station, to a user, typically a mission control system. The provided parameters are ASN.1 / BER [6] encoded and follow the Functional Resource definitions registered at SANA (but are not defined in the CSTS Monitored Data Service [2][†]). For that reason, the SANA registry hosts in addition to the human readable Functional Resource registry a corresponding ASN.1 file, which is ready to be used for the encoding and decoding of Functional Resource parameters and events as transferred by the CSTS Monitored Data Service.

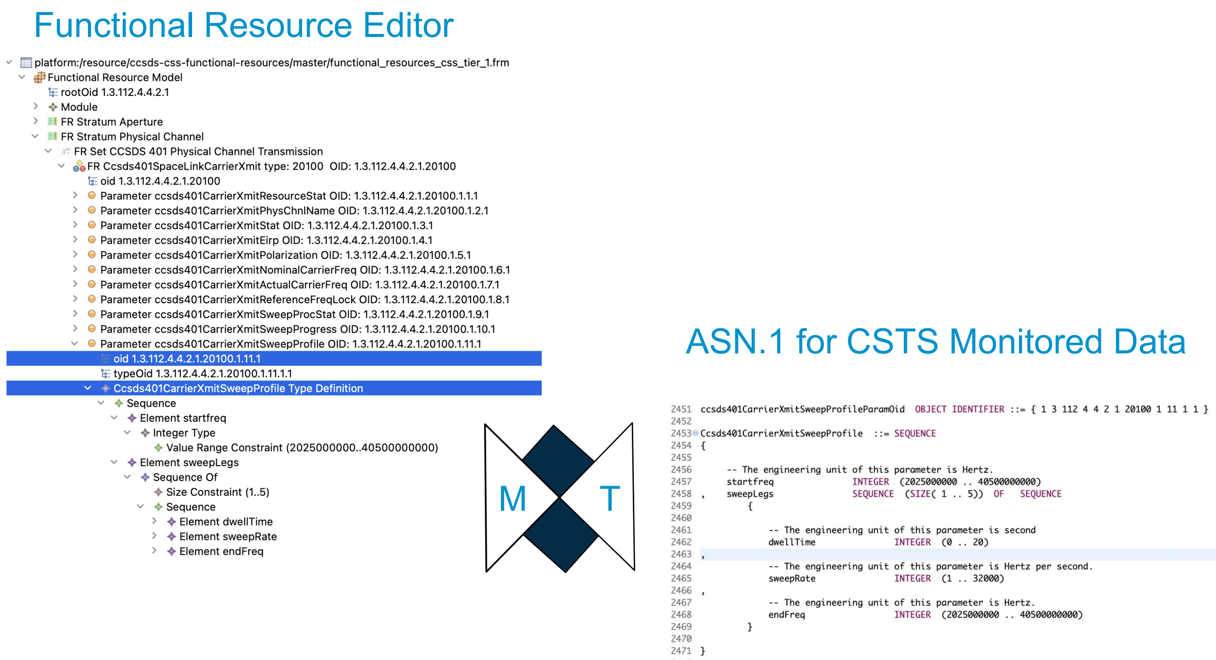

Figure 4 Functional Resource to ASN.1

Figure 1 illustrates the above with a practical example. For the parameter ccsds401CarrierXmitSweepProfile, two ASN.1 constructs are generated:

- `ccsds401CarrierXmitSweepProfileParamOid` – the OID identifying the parameter
- `Ccsds401CarrierXmitSweepProfile` – the type definition of the parameter

It is assumed and recommended that CSTS Monitored Data service implementation make use of the ASN.1 file hosted at SANA as part of the Functional Resource registry. In that way consistency with the SANA Functional Resource model is ensured.

It can be observed that a convention is used to allow the association of the OID of a parameter and the corresponding type definition. The OID of a parameter has the name of the parameter and is suffixed with 'ParamOid'. In addition, the parameter OID must start lower case and the parameter type definition uppercase. The use of such conventions is not ideal but is required by the way ASN.1 works. Here also the model-based approach to Functional Resources helps; the automatic ASN.1 generation ensures that the convention described above is implemented without any exceptions, this is of practical relevance. The ESA implementation of the CSTS Monitored Data Service reflects the code generated by the ASN.1 compiler and associates parameter type definitions to OIDs which have the same name and the suffix 'ParamOid'.

[†] In fact, the CSTS Monitored Data book [2] does not contain a single definition of a monitoring parameter. It does however specify how Functional Resource parameters can be monitored in a generalized way.

6. Use Case: Monitoring and Control Model

Most ground station network providers use central Monitoring and Control (M&C) systems monitoring all equipment of a ground station. Such a system typically aggregates monitoring parameters of several ground station equipment like the antenna, modem and others and present a holistic view of the station to operators‡. The same is true for controlling and automating operations - the station M&C system is typically able to control all equipment in a ground station, thus allowing to implement overall automated operations. Often ground station M&C systems are generic and are adapted to specific equipment by means of an equipment specific model, which is prepared offline. At ESA/ESOC this process is called tailoring and the tailoring team aims at keeping the tailoring as similar as possible for all supported ground stations.

Such an approach becomes quickly complex when ground stations comprise equipment from different manufacturers. Functional Resources offer the ability to implement an equipment independent monitoring and control layer on top of the proprietary equipment dependant layer.

The clear advantages are a unified M&C view on ground stations, no matter what underlying equipment is used. Such a unification has a huge potential to simplify operations and automation; equipment specifics and differences are abstracted and not visible to operators. It is furthermore suggested to base automation on this equipment independent layer, to simplify the complexity of automation and promote the portability of automation procedures.

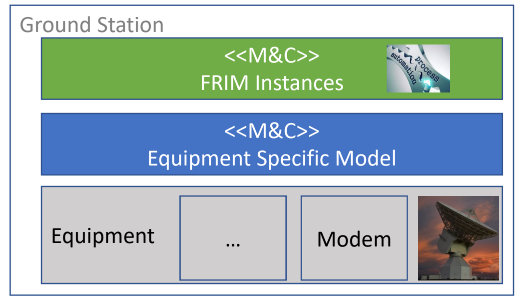

Figure 5 Functional Resource Instance Model

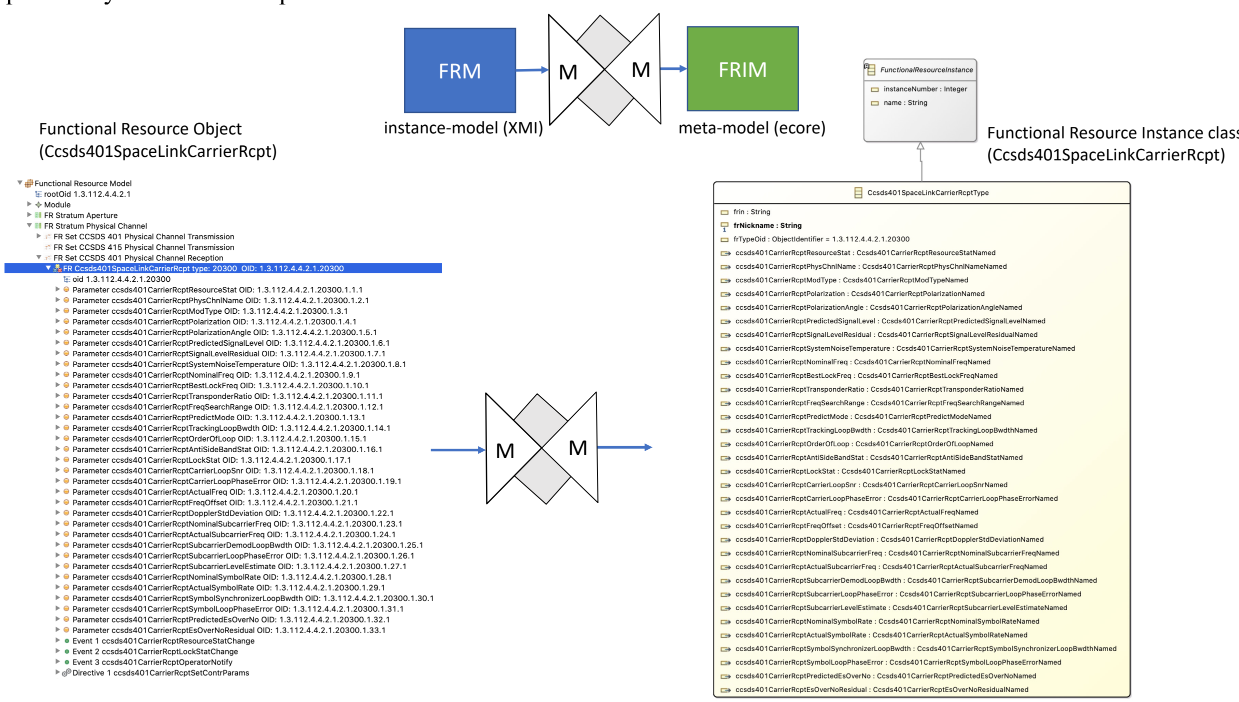

Figure 6 Functional Resource to Functional Resource Instance Transformation

To make the best use of Functional Resources, it is suggested to realize the equipment independent M&C layer discussed above with Functional Resource Instances. A Functional Resource Instance (meta / ecore) model can be automatically created by a M2M transformation of the Functional Resource Model to a Functional Resource Instance

‡ Clearly also centralized M&C systems at network level are used. The current discussion is also applicable also on network level, perhaps it is even more important at network level.

model as depicted by Figure 6. The underlying principle is as follows: every Functional Resource, which is technically speaking an object in the Functional Resource Model (FRM), is transformed into a Functional Resource Model Instance class; these classes form the Functional Resource Instance Model (FRIM). This is illustrated at the example of the Ccsds401SpaceLinkCarrierRcpt in Figure 6. Such an automatic M2M based approach ensures that all Functional Resource definitions are used consistently for Functional Resource Instance classes. Clearly, updates of the Functional Resource Model must be propagated to Functional Resource Instance models.

The resulting Functional Resource Instance Model can be used in a modelling tool to model in a type safe and consistent manner all Functional Resource Instances required to represent functions of the real ground station equipment. In the presented example of the Ccsds401SpaceLinkCarrierRcpt, which typically represent a demodulator function realized by a modem, for a ground station with four demodulators, four Ccsds401SpaceLinkCarrierRcpt instances would be created.

Finally, the instantiated parameters, events and directives of Functional Resource Instance must be bound to the real ground station equipment. Such a binding of Functional Resource Instances should be well possible, as such a binding is scoped to individual functions typically provided by one equipment.

It is also worth mentioning that some Functional Resource Instances may be created and destroyed dynamically at runtime. SLE Service Instances may be an example for dynamic Functional Resource Instances. Such dynamic behaviour can be supported by creating in addition to Functional Resource Instance classes corresponding container classes for the FRIM model. The FRM can in turn provide annotations to drive such a FRIM container generation; however, also other approaches like a systematic FRIM container class generation could be envisaged.

7. Use Case: Configuration Profiles

When the CCSDS Area started the work on the Functional Resource Model, the first goal was to provide Functional Resource definitions with parameters, events, and control directives for the CSTS Monitored Data Service and the upcoming CSTS Service Control service. These two services provide online monitoring and control of ground stations in an interoperable way and rely on Functional Resources[1] for parameter and directive definitions. During that work it was quickly realized that many parameters are in fact not only monitoring parameters, but that they are also configuration parameters. In fact, it is the other way around, often configuration parameters are subject to monitoring.

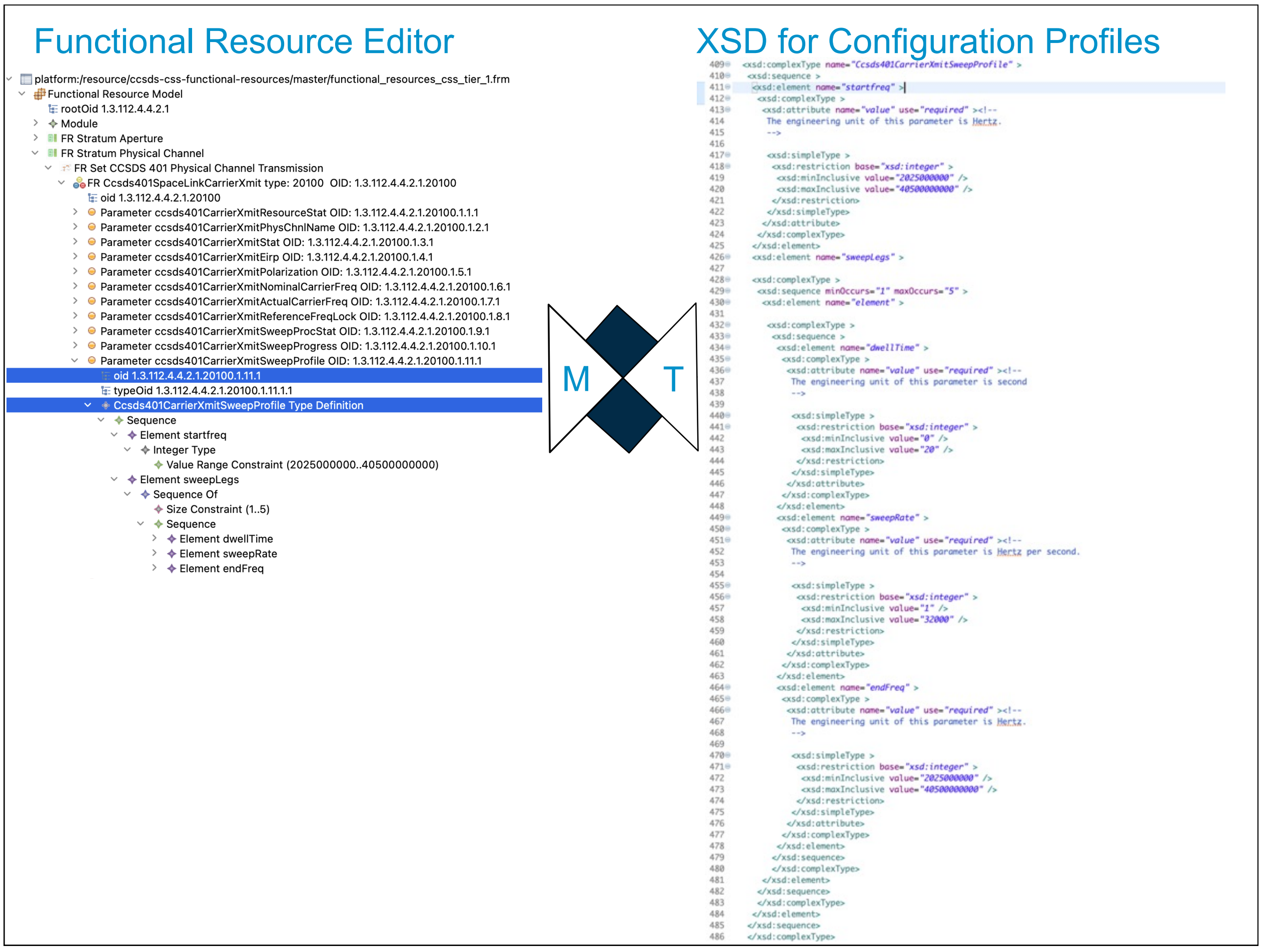

Figure 7 Functional Resource transformation to XSD

To avoid reinventing the wheel i.e., specify the same parameter as a Functional Resource parameter for online monitoring and again as a configuration parameter for Configuration Profiles, the CSS Area came up with the idea to transform the configuration parameter of the Functional Resource Model into XML schema definitions (XSD). When using the generated XSDs to define configuration profiles, it is of course possible to refine constraints on parameters to finally obtain a configuration which is valid to configure a ground station to support a specific spacecraft.

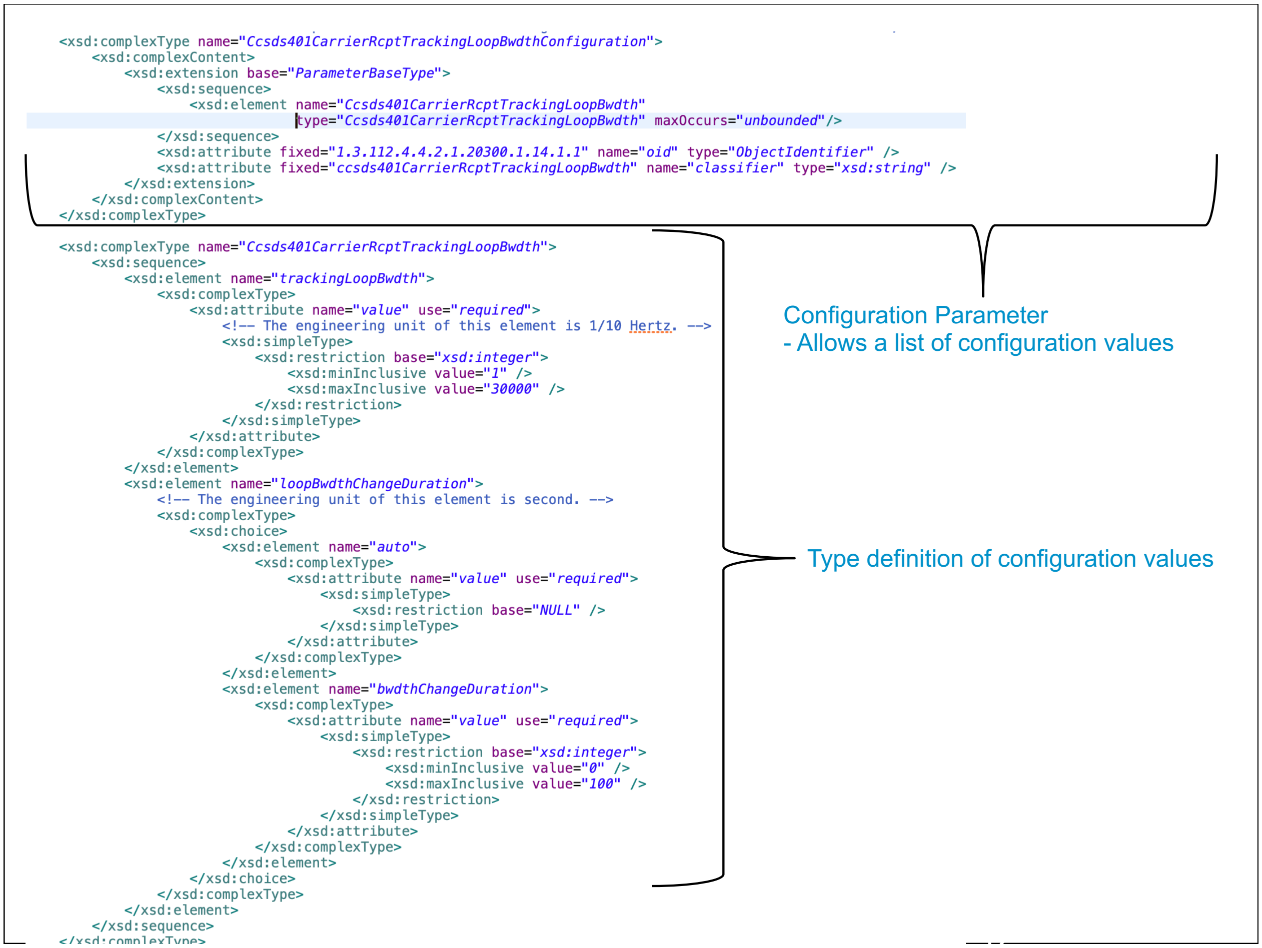

Figure 8 Configuration Parameter Definition generated from FRM

Figure 8 shows an example of a configuration profile parameter as generated from the Functional Resource Model to capture in the context of a mission all possible values for the loop bandwidth of a tracking receiver. Technically *Ccsds401CarrierRcptTrackingLoopBwdthConfiguration* defines the configuration parameter holding a list of possible configuration values of *Ccsds401CarrierRcptTrackingLoopBwdth.* The latter is actually a complex type defining the actual *trackingLoopBwdth* and the associated *loopBwdthChangeDuration.*

The presented approach is another example, how the Functional Resource Model is the single source of information, here for ASN.1 definitions of parameters for online monitoring and the corresponding XSD definition for configuration purposes. Consequently, the consistency of monitoring parameters and configuration parameters is ensured. Both are derived from the Functional Resource Model.

8. Relation to Electronic Data Sheets

The CCSDS Engineering Steering Group (CESG) has acknowledged and endorsed the approach of Functional Resources as an abstract, yet precise information model underling the terrestrial services to configure and monitor ground stations. In 2022 CESG remarked that in fact quite some functions realized by a ground station are in principle also realized on board of a spacecraft. Examples are modulator / demodulator, encoder / decoder, but also higher-level protocols like CFDP entities or Bundle Protocol nodes are potentially realized on board of spacecrafts and on ground.

The Functional Resource model with its underlying model-based tooling produces precise descriptions of parameters, their types including constraints for ranges, valid values and more. CESG suggested to extend that approach to model also data types for PDU by means of Functional Resources. An extension of the Functional Resource editor has been implemented and demonstrated at the example of a Bundle Node the capability to model also data structures for Functional Resources.

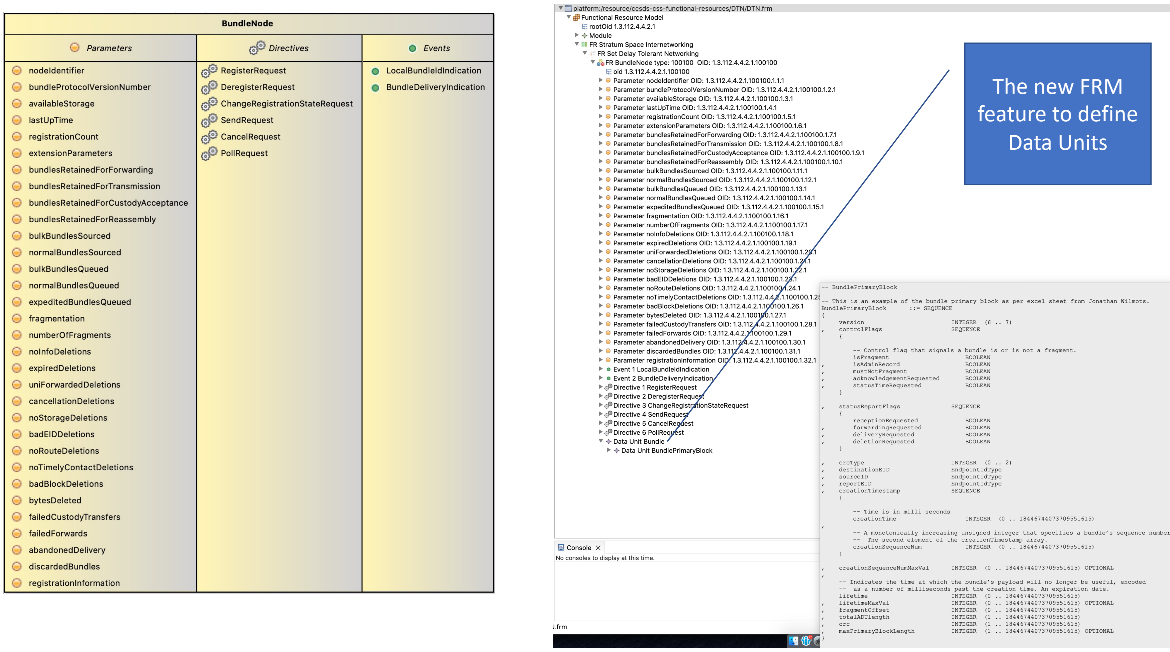

Figure 9 Functional Resource Editor modelling of Data Units

As shown in Figure 9, the relatively complex data structure Bundle Primary Block has been modelled by means of the Functional Resource editor. Such Data Unit definitions can be exported, a candidate of a suitable export format is XSD. A first CESG assessment confirmed that the expressiveness and precision is suitable and superior to many CCSDS Recommended Standards, in addition the Functional Resource model provides machine readable data format definitions – this is clearly not easily the case for the documents used to capture CCSDS recommended standards.

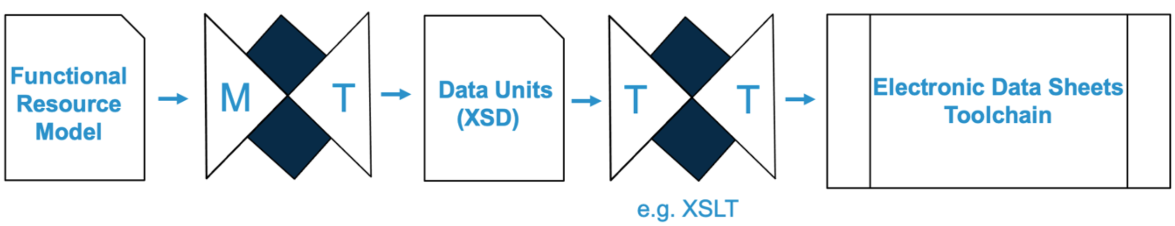

Figure 10 Functional Resources and Electronic Data Sheets

The XSD export is supported by the Functional Resource editor out of the box and is a clear machine-readable format. As illustrated by Figure 10, one discussed idea is to hook up Functional Resource definitions of input and output data with Electronic Data Sheets (EDS). For Electronic Data Sheets toolchains exist, which can generate code and other artifacts facilitating the development of on-board components, but among others, EDS require an XML based definition of the input and output data.

The final goal is to facilitate a Model Based System Engineering tool chain, replacing classical document specifications when developing on-board equipment.

9. Model Based System and Operations Engineering Context

The adoption of model-based engineering techniques for the Functional Resource modelling can be put in a broader context of model-based approaches in the areas of system as well as operations engineering. Particularly, ESAs on-going development of the Ground Station Monitoring and Control System Based on Common Core Software (GSMC-CC) can be highlighted with this respect. GSMC-CC will provide a next generation M&C system based on the

European Ground Systems – Common Core (EGS-CC) infrastructure for all ESA ESTRACK ground stations. The EGS-CC Tailoring Data Model (TDM), which was previously called Conceptual Data Model (CDM), has been elaborated following a model-based approach, and is in fact also based on EMF Ecore. The OPEN-S ground station tailoring environment for GSMC-CC is based on the Open Preparation Environment (OPEN), which offers a generic platform for building tailoring applications for EGS-CC based systems. OPEN and respectively OPEN-S use heavily EMF for the tailoring data editors and viewers. Thereby, it is important to highlight that the TDM has been developed based on the ECSS-E-TM-10-23A technical memorandum covering the space system data repository concepts. The TDM makes a clear separation between the monitoring and control (M&C) of a system and the actual product tree of a system with respect to physical decomposition in terms of hardware and software resources. The product structure is defined through the Space System Model (SSM), whereas the monitoring and control system decomposition is defined through the Monitoring Control Model (MCM), both being distinct but interrelated parts of the TDM. Thereby, the M&C structure can be different from the structure of the underlying physical resources. The MCM comprises a hierarchy of Monitoring and Control Elements (MCEs) that contain aspects such as activities, parameters, and events. This approach is very similar to the approach taken by Functional Resources as abstract, functional representation of the system (ground station and equipment) with respect to the M&C. A conceptual mapping between Functional Resources and the TDM MCM can be derived. Such a mapping and extensions of the GSMC-CC software including the operations and the tailoring environments have been covered under a study on Cross Support Services Extension Component for integration in Mission Control System infrastructure based on EGS-CC, in short CSS study. A follow-on study on Service Oriented Ground Stations Network Configuration and Resource Allocation has been started recently to cover any identified gaps and analyse more closely the possibility to have fully FRM compliant ground stations tailoring and operations. In this context, the utilization of novel solutions from the ESA Model Based System Engineering (MBSE) domain are being evaluated. Particularly, the ESA MBSE strategy covers two main pillars: (i) a common Space System Ontology (SSO) aiming to establish common semantics for the exchange of engineering data across the overall space system engineering lifecycle; (ii) a Model Based Engineering Hub (MBEH) providing infrastructure for the engineering data exchange in line with the SSO. While different MBEH flavours are being developed by two different consortia to de-risk the respective area, one of the developed MBEH systems supports having multiple data model increments (or versions) along with multiple versions of associated data sets within the same MBEH instance. For clarity, the term ‘data model’ is equivalent to ‘meta-model’ and the term ‘data’ (or ‘data set’ as a grouping construct) is equivalent to a ‘model’ as an instantiation of the ‘meta-model’. Different versions/increments can occur for both, a data model and the associated data sets, however they need to be managed in different ways. Ultimately, the introduced MBEH system can offer an environment, where FRM, FRIM, and TDM data model increments and associated data sets can co-exist and be managed in a consistent and interrelated way. A trial based on the import of a specific TDM version along with real-life ground station subsystem Mission Information Base (MIB) in TDM format into the MBEH has been completed successfully. The subsequent efforts will be focused on supporting FRM and FRIM data model increments and associated data sets as well as interrelation between the various data and export of relevant operational products such as operations tailoring data and configuration for the operations systems. In fact, the MBEH features powerful M2M transformation features for transitioning engineering data between different phases of the space system engineering lifecycle, i.e., in line with associated underlying data models supported by various domain specific engineering tools. The FRM transformations described in the previous sections for the derivation of FRIM to be used for M&C, configuration profiles, or data units and EDS can be realized in an extended MBEH flavour to provide a single-entry point for the ground station system and operations engineering in a modern, web-based, scalable, multi-user environment.

10. Conclusion and Future Work

In this paper we have introduced the concept of Functional Resources, representing the monitoring and control aspects of ground station equipment as an abstract, yet precise information model. We have shown how a model-based approach to author Functional Resources has enabled the CCSDS Cross Support Transfer Area (CSS) to manage all information of Functional Resources efficiently and precisely. On top, the presented model-based approach has eased the generation of additional products out of the Functional Resource Model:

- ASN.1 definitions to facilitate implementations of the CSTS Monitored Data Service
- A Meta model to create Functional Resource Instances representing ground stations
- XML schema definitions for Configuration Profiles for Functional Resource Instances

In addition, we have shown the currently discussed relation of Functional Resources to Electronic Data Sheets. That discussion confirms the approach of Functional Resources representing in a precise, abstract way functions of real-world implementations, although this time in the domain of on-board components. It underlines the power of the selected model-based approach with a clear underlying meta model, rendering the Functional Resource Model machine readable and transformable.

The evaluation of the benefit using Functional Resources in the context Space to Ground ICDs is left to a future analysis. The expectation is that the parameters as expressed by Functional Resources may be used in a model-based formal way to generate at least parts of Space to Ground ICDs. The expected benefit is that these machine-readable models for the Space to Ground ICD facilitate validation and processing by tooling, e.g. to generate consistent configuration profiles out of the Space to Ground ICD (model). There is a clear relation to the use case of configuration profiles described above.

Finally, JAXA and ESA have announced the implementation of the CSTS Monitored Data Service making use of Functional Resources, which is to our knowledge the first operational adoption to Functional Resources. However, it is expected that Functional Resources are not only beneficial for cross support. Functional Resources have the potential to increase efficiency for organisations operating large scale ground station networks with the introduction of an equipment intendant abstraction for ground station monitoring and control.

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