When the Space Gets Cloudy

A Systematic Assessment of Cloud Computing Application Domains for ESA Ground Data Systems

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The European Space Agency has conducted in 2011 a research and development study at the European Space Agency, ESA, to analyse how Cloud Computing paradigm can best be utilised to address some of the challenges of modern ground data systems, such as increased distribution, increased demand on computing resources, increasing effort required for maintenance and deployment of an ever growing number of operational software and infrastructure baselines, increased demand on software flexibility in terms of fast adoption of evolving operational requirements, increased complexity of Intellectual Property Rights (IPR) management, increased expectation on reduced time-to-the-market along with continuous emphasis on reducing the development, maintenance and operation costs of ground data systems. The objectives of the study have been: Identification of candidate ground data systems for each Cloud Computing service-provisioning model. For this purpose an analytic tool has been developed which utilises a set of metrics for systematic evaluation of the so-called "cloudability" level of the analysed applications; Assessment of suitability of different Cloud deployment models, i.e. private clouds, public clouds or hybrid clouds for each identified application domain; Analysis of how and to what extent the private Cloud Computing paradigm can address the security requirements of ground data systems; Evaluation of open source and commercial off-the-shelf Cloud provisioning solutions for establishing a private Cloud; Definition of a roadmap for evolution of the existing virtualized environment at the ESA European Space Operations Centre towards a private Cloud, including the identification of the required changes to existing business processes and the relationship between different organisational units within the Agency; The study has been successfully concluded in 2011 with the results of the assessment analysis and a Proof of Concept (PoC) demonstrator of the envisaged private Cloud for ground data systems. Our paper elaborates on the results of the study and devises how the existing ground data systems can benefit from Cloud Computing at infrastructure, platform and application level.

I. Introduction

A. Ground data systems background

Ground data systems constitute an important element of every space mission. The term ground data system is a generic umbrella-term used for referring to all software systems involved in the ground operations of a space mission. Typical ground data systems in traditional operation scenarios are the spacecraft monitoring and control

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system, ground station and network monitoring and control systems, a number of planning systems (e.g. payload, spacecraft ground station network planning), data distribution systems and simulators. This is not an exclusive list but an example of major components of a ground segment.

ESA ground data systems are typically developed based on the reuse and customisation of generic and multi-mission software infrastructure. SCOS2000 [4] and SIMULUS [5] are key elements of such generic ground data systems Infrastructure.

B. Cloud Computing Background

The most recognised definition for Cloud Computing was published by the National Institute of Standards and Technology (NIST) [Ref. 2]. It classifies an IT solution as a Cloud Computing solution when it exhibits the following five essential characteristics according to [Ref. 2]:

- "It enables **on-demand self service**: Users are able to provision, monitor and manage computing resources as needed without the help of human administrators;
- It has **broad network access**: Computing services are delivered over standard networks and heterogeneous devices;
- It provides **rapid elasticity**: IT resources are able to scale out and in quickly and on an as-needed-basis;
- **Resource pooling** is part of it: IT resources are shared across multiple applications and tenants in a non-dedicated manner;
- It is a **measured service**: IT resource utilization is tracked for each application and tenant, typically for public Cloud billing or private Cloud chargeback."

An IT solution qualifies as a Cloud Computing solution, only if it posses all the above characteristics. Beyond these essential characteristics, Cloud Computing solutions are often further categorised with respect to two main criteria, their deployment model and their service-provisioning model.

Cloud Computing Deployment Models according to NIST [Ref. 2]:

- **"Private Clouds**: The Cloud infrastructure is operated solely for an organization. It may be managed by the organization or a third party and may exist on premise or off premise;
- **Public Clouds:** The Cloud infrastructure is made available to the general public or a large industry group and is owned by an organization selling Cloud services;
- **Community Clouds**: The Cloud infrastructure is shared by several organizations and supports a specific community that has shared concerns (e.g., mission, security requirements, policy, and compliance considerations). It may be managed by the organizations or a third party and may exist on premise or off premise;
- **Hybrid Clouds**: The Cloud infrastructure is a composition of two or more clouds (private, community, or public) that remain unique entities but are bound together by standardized or proprietary technology that enables data and application portability (e.g., Cloud bursting for load-balancing between clouds)."

Cloud Computing Service Models according to NIST [Ref. 2]:

- "**Software as a Service (SaaS), also known as Application Services**: The capability provided to the consumer is to use the provider's applications running on a Cloud infrastructure. The applications are accessible from various client devices through a thin client interface such as a web browser (e.g., web-based email). The consumer does not manage or control the underlying Cloud infrastructure including network, servers, operating system, storage, or even individual application capabilities, with the possible exception of limited user-specific application configuration settings;
- **Platform as a Service (PaaS)**: The capability provided to the consumer is to deploy onto the Cloud infrastructure consumer-created or acquired applications created using programming languages and tools supported by the provider. The consumer does not manage or control the underlying Cloud infrastructure including

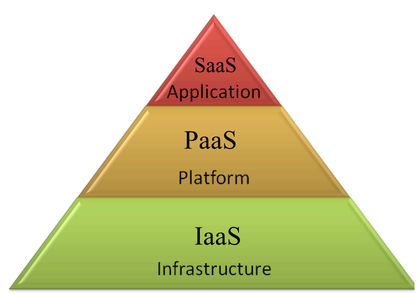

Figure 1: Cloud Computing Service Models

network, servers, operating systems, or storage, but has control over the deployed applications and possibly application hosting environment configurations;

- **Infrastructure as a Service (IaaS)**: The capability provided to the consumer is to provision processing, storage, networks, and other fundamental computing resources where the consumer is able to deploy and run arbitrary software, which can include operating systems and applications. The consumer does not manage or control the underlying Cloud infrastructure but has control over operating system, storage, deployed applications, and possibly limited control of select networking components (e.g., host firewalls)."

It is worth noticing that the Cloud Computing service provisioning models build a hierarchical structure, often referred to as the Cloud Computing Pyramid, where the services of the higher layer relay on the capabilities provided by the lower lever service models. In other words, a Cloud Computing Solution with a SaaS service provision most be deployed itself on a PaaS or an IaaS, as illustrated in Figure 1.

C. Cloud Computing at European Space Operation Centre

The European Space Agency has conducted in 2011 a research and development study at ESOC to analyse how Cloud Computing paradigm can best be utilised to address some of the challenges of modern ground data systems.

Before embracing into a Cloud Computing initiative, it is essential for every organisation to first identify the problems, specific to its own IT landscape, which shall be addressed by adaptation of the Cloud Computing paradigm. As a second step a systematic suitability analyses of the business processes, applications and services in questions can reveal the best candidates for each Cloud Computing service and deployment model.

The objectives of our study have been defined accordingly:

- Identification of candidate ground data systems for each Cloud Computing service provisioning model.
- Assessment of suitability of different Cloud deployment models for each identified application domain;
- Analysis of how and to what extent the private Cloud Computing paradigm can address the security and data confidentiality o requirements of ground data systems;
- Evaluation of open source and commercial off-the-shelf Cloud provisioning solutions for establishing a private Cloud;
- Definition of a roadmap for evolution of the existing virtualized environment at ESOC towards a private Cloud, including the identification of the required changes to existing business processes and the relationship between different organisational units within the Agency;

The study has been successfully concluded in 2011 with the results of the assessment analysis and a Proof of Concept (PoC) demonstrator of the envisaged private Cloud for ground data systems.

II. Problem Domain Analysis for Ground Data Systems

The continuous technological advancements in the space programmes of the European Space Agency, ESA, introduce new challenges on the development, deployment, maintenance and operation of the ground data systems. The following list highlights a number of specific aspects in modern ground data systems:

D. Distribution and location independency of ground data systems

With technological advancements of space missions the complexity of the ground segment of space programs is continuously increasing. This increase of complexity is best revealed in the growing number of involved ground data systems and the large number of not seldom geographically distributed operation and service provision centres of some space programmes. The political dimension and the boundary conditions of some strategic programmes such as the Galileo and the European Space Situational Awareness (SSA) Programmes add on the complexity of the ground data systems, by breaking down and distributing the elements of the ground segment, traditionally tightly integrated and hosted in one single data centre, in a number of geographically distributed operation and data/service provision centres.

The location transparency and the on-demand resource allocation of Cloud based solutions make Cloud Computing a promising paradigm for addressing the above-mentioned requirements of modern ground data systems.

E. High Availability of ground segment services and space mission products to the user community

The functionality of the software applications involved in classical ground segments of space missions are typically focused on safe operation of spacecraft and with the provision of a manageable set of data products to a select user community of experts. Space programmes are however undergoing in the recent years a transition from being an isolated and primarily scientific-oriented domain to becoming more and more an integrated element of larger System-of-Systems, serving much broader user communities of various application domains. The Integrated Applications Programmes of ESA and the European SSA Programme are good examples of this evolution. The functionalities of ground data systems of these programmes extend the classical spacecraft operation with multiple domain specific software applications and involve provision of a broad palate of services and higher level, added-value products to a diverse user community for each domain. The timely provision of these high-quality services and products to a much larger and diverse community (often via the Internet and through rich web-based applications), introduce new requirements on high-availability and ease of access of the related services.

The broad network access and rapid elasticity are two of the five essential characteristics of Cloud Computing paradigm [Ref. 2] making Cloud based solutions intrinsically highly available solutions with network-based access. So-called Cloud services also focus on simplicity as a key feature, to increase user satisfaction hence his stickiness to the provided service.

F. Performance, scalability and increasing demand on computing resources

The continuous advancement of the computing capabilities of new spacecraft along with increasing speed of the space to ground communication links through utilization of higher frequencies allow the generation, processing and transfer of significantly larger amount of data from the spacecraft to the ground. This brings about increasing demands on computing resources to respond to the challenging performance requirements on ground data systems for transferring, processing and storage of ever-growing amount of data on the ground.

Many ground data system processes are automated, data driven tasks, which are only executed upon availability of the triggering data (e.g. when spacecraft telemetry or data from ground based radars or telescopes is received), hence releasing the computing resources after their termination. Ground data systems of each space mission are however developed traditionally in isolation and deployed on dedicated hardware resources, which are often seized to satisfy the performance requirements at peak times of worst-case operational scenarios. The peak times often represent however a small fraction of the operational lifetime of the systems.

Rapid Elasticity, which refers to on-demand dynamic scalability of provisioned computing resources, is at the core of Cloud Computing solutions. Cloud Computing solutions provide more computing resources with increasing demand in a dynamic and transparent manner to the consumer.

In the Cloud Computing paradigm, IT resources are shared across multiple applications and consumers in a non-dedicated manner. This concept is referred to as Resource Pooling. Cloud Computing solutions provide moreover Measured Services, for which the exact utilisation of the computing resources are tracked and often used for billing purposes.

G. Utilisation of end-to-end Off-The-Shelf solutions for non-space-domain-specific tasks

An increasing number of custom developed software components of modern ground data systems have been replaced by commercial or open source off-the-shelf software solutions in respond to a number of higher level business goals:

- Reduction of development, deployment, maintenance and operation costs of ground data system;

- Increase of ground data systems flexibility in responding rapidly to the change of operational requirements (faster time to the market)
- Leverage the technology advancements from other industry domains

In few extreme cases custom developed standalone applications, used in ground segment and its supporting processes can be entirely replaced by off-the-shelf alternative solutions from the mainstream IT domains. The primarily target of this transition are the supporting tools used during software development, operation and maintenance of ground data systems, which are very often not specific to the space domain. To give some examples:

- The software development and lifecycle management tools (software project management and configuration control tooling, IDEs, requirement Management tooling, source code repositories and build management tooling, software testing and validation tooling, software packaging, deployment management and monitoring tooling)
- The infrastructure for establishment and operation of service desks for support and maintenance of ground data systems (incident and issue tracking, ticketing, support provisioning and reporting tools)
- The infrastructure for hosting web-portals and web-based applications
- Security infrastructure (firewalls, Security Gateways, Encryption/Decryption services, Certificate management infrastructure such as certification server and repository)
- Databases, backup and storage infrastructure
- Messaging and communication infrastructure and service busses
- Generic purpose utility services at application level, which are involved in many ground data systems such as data product distribution solutions, file transfer and management, notification services, visualisation, reporting, health and performance monitoring data format and data model transformation services

The Software-as-a-Service (SaaS) Cloud Computing model is the next step in the natural evolution of software reuse, which represents very promising approach towards addressing the cost reduction and increased flexibility requirements of ground data systems. CloudBees [Ref. 15] is an example of such type of tooling for software development lifecycle.

H. Federation of disperse solutions, System of Systems and Moving towards Service Oriented Architectures

One particular aspect of the mentioned evolution of space programmes towards System-of-Systems (SoS) of which the space element is only one component among others is the aspect of distributed ownership and governance of the involved software assets. In such ecosystems software applications from entirety different domains must be federated to compose a higher-level solution at SoS level. The important aspect hereby is that each component may be owned and their evolution governed by a different entity.

The very same aspects are given in the case of cross-organisation ground data systems of multi-national space missions or in the context of international space collaborations across national space agencies.

Service Oriented Architecture, SOA, is a paradigm, which is often adopted to address these very challenges. OASIS[5] describes Service Oriented Architecture as a "paradigm for organizing and utilizing distributed capabilities that may be under the control of different ownership domains. SOA is a means of organizing solutions that promotes reuse, growth and interoperability. It is not itself a solution to domain problems but rather an organizing and delivery paradigm that enables one to get more value from use both of capabilities which are locally "owned" and those under the control of others. It also enables one to express solutions in a way that makes it easier to modify or evolve the identified solution or to try alternate solutions."

The ESA ground data systems are evolving step by step towards component based composite applications and service oriented architectures. Elements of the ESA ground data systems provide their functionality in form of services to other elements and to the end user. The granularity of the services is diverse and depends on the subject elements. In some cases however the functionality of a "standard" element of the ground data systems as a whole can be provided as a service (Software as a Service, Saas).

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[5] OASIS is the abbreviation for Organization for the Advancement of Structured Information Standards

Service Oriented Architectures are often implemented on SOA middleware, such messaging infrastructure, Enterprise Service Bus (ESB), service registry, business process and orchestration engines. Some of these elements could be provided in form of Platform as a Service, PaaS, on the Cloud, so that services could be directly deployed to them. SOA and Cloud Computing are moreover complimentary technologies and/or approaches when delivering modern IT solutions. SOA is seen by many as one of the main enabling technologies for Cloud Computing and Cloud Computing is considered intrinsically service oriented. Adoption of SOA for ground data systems can significantly facilitates the transition to the Cloud.

I. Increased awareness for security aspects and risk management

The aspects of security and data/service location are increasingly taking a prominent role in the design, development, validation, deployment and operation of ground data systems. For a number of ESA programmes such as the Galileo and the SSA programmes these aspects are among the prime design drivers of the system.

The questions of security assurances and compliance to data location and governance policies are among the most critical points for many organisations when assessing Cloud Computing solutions. It goes without saying that not every application in the ground data system domain is a suitable candidate for transition to a public Cloud. It is however worth noticing that in contrary to the initial intuitive suspicion towards Cloud based solutions, Cloud Computing solutions can in many cases increase the level of security compared to custom-developed applications, deployed to in-house managed data centres. The source of this surprising fact lays simply in the “economy of scale” of large data centres of major Cloud vendors such as Amazon, Google or Microsoft, which can afford a much more sophisticated and largely automated security ensuring mechanisms when compared to the limited human and IT resources available in traditional data centres of each organisation.
In order to address national and regional regulations on data confidentiality and data location many Cloud Vendors have started establishing dedicated data centres in specific geographic locations (US, Europe, Asia). Depending on the size of the envisaged Cloud solution and the position of the customer specific governance requirements can be negotiated as part of the Service Level Agreements (SLA)s even with the public Cloud vendors.
The private, hybrid and community Cloud deployment models have been moving more into the focus of larger organisations and vendors in the recent years, as they can combine the benefits of the Cloud Computing paradigm with the requirements of on-premises deployment of services and storage of the related data.

J. Provision and management of a large number of infrastructure and ground data system baselines

ESA ground data systems are typically developed based on the reuse and customisation of generic and multi-mission software infrastructure. The ground data systems infrastructure components utilise in turn often third party commercial and open-source off-the-shelf libraries, products and platforms, which again relay not seldom on certain operating system add-on packages and features. The management of the hardware and software configuration, IPR and licensing information, versioning and baselines governance for all involved elements of a complete ground segment is one of the major challenges of the modern ground data systems. This challenge is amplified by the longevity of space-missions and the general conservative approach towards migration of ground data systems of a flying mission to newer versions, mainly due to the risk reduction and validation effort associated with the migration of ground data systems. As a result multiple versions of each component must be maintained in parallel and strict change and baseline management governance rules applied.

The dynamic provisioning concepts and the tools utilised in the domain of Cloud Management, facilitate the definition, storage and management of custom-defined templates and baselines. Modern provisioning tools support automated deployment of the elements of the custom specified templates. Moreover the PaaS and SaaS Cloud service models eliminate the need for revalidation of the reused software and in particular integration testing as they introduce a new reuse paradigm, which is essentially different to the the traditional concept of software component and software libraries reuse. This is known today as Infrastructure as Code or DevOps [Ref. 16] in the IT world.

III. Cloudability Assessment Approach and Results

Figure 2 illustrates the stepwise assessment approach, adopted during the study, for evaluation of the cloudability of ESA ground data systems. It is based on an elaborated set of metrics, which have been devised specifically for this purpose. It comprises the analysis of suitability for various combinations of Cloud Computing service-provisioning and Cloud deployment models. It also takes into account risk assessment in support the decision making process.

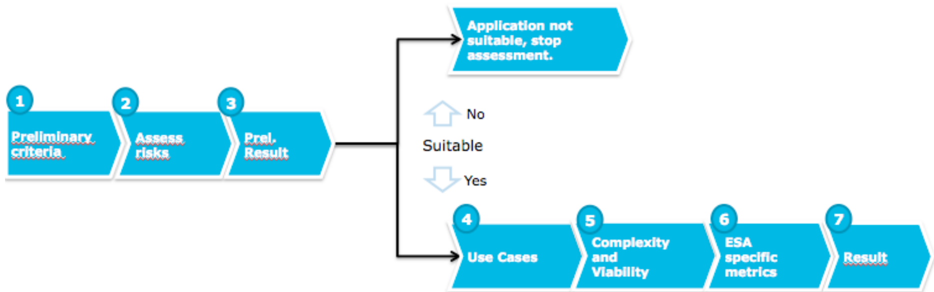


Figure 2. Assessment approach.

The process is composed of seven sequential steps:

1. A preliminary scoring scheme is used for rapid analysis of the ESA ground data systems portfolio
2. Risk assessment is performed as part of the initial assessment (Risk veto technical suitability)
3. Selection of candidate ground data systems for further detailed "cloudability" analysis
4. Selected applications are used to identify application styles and typical usage scenarios
5. Elaborated complexity and viability metrics are specified and populated for each selected application
6. The operational scenario, the metric will roundup the assessment
7. Final result

The execution of the processes has been supported by a custom developed cloudability assessment tool, which has been populated with the assessment metrics

A. Identification of candidate ground data systems

Given the rich application portfolio of ESA ground data systems, the first step of the "cloudability" analysis has focused on the identification of the most promising candidate applications for further detailed assessment. The application portfolio analysis has been performed with the support of Cloud Computing experts from the industry, using a simple ranking mechanism, with only 10 high-level suitability criteria and risk assessment metrics. The concentration on a manageable number of metrics at this stage of the process, proved to be very effective for performing a rapid pre-assessment and identification of high potential applications.

The criteria and risk assessment metrics used for this purpose have been directly devised from the ground data systems problem domain analysis, presented in the previous section.

As a result of this first evaluation round, components from the two main groups of ESA ground data systems were identified as suitable candidates for further detailed analysis, i.e. components of ESA generic multi-mission ground data systems infrastructure EGOS as well as a customised instance of the operational simulator and mission control system of a particular space mission.

Suitability for further Assessment 71%

Level		Score	Description
Very High	Up to	100%	The application should be further assessed
High	Up to	75%	The application should be further assessed
Medium	Up to	50%	The application should be put in a backlog for future assessment
Low	Up to	25%	It is not recommended to further assess this application
None	Equals to	0%	It is not recommended to deploy and/or migrate the application to the cloud

Figure 3. Cloud Suitability

B. Detailed Assessment of suitability of different Cloud Computing service and deployment models

The detailed assessment of selected applications has further grouped the applications by their suitability per service provisioning model and Cloud deployment model. It is worth mentioning that suitable candidates have been identified among ESA ground data systems for all three service-provisioning models. Also for each Cloud deployment model valid use cases have been identified. To give some examples:

- The ESA simulation infrastructure SIMSAT has been identified as a good PaaS candidate, as it provides a run-time simulation environment, on which packaged simulation models could be deployed. The SIMSAT platform is a specially interesting candidate as the services provided from the simulation environment are standardised and the interfaces between the simulation environment and simulation models well specified;
- Some of the SCOS2000 components such as the Packet, Parameter and File Archive have been identified as SaaS candidates as their customisation for missions is mainly based on configuration rather than code modification;
- The SSA Space Weather Service Provision Portal has good PaaS as it represents a platform on which Space Weather service providers could deploy their services [1]

IV. ESA ground data systems and the private Cloud

One of the distinct objectives of the study has been to analyse the utilisation scenarios of a private Cloud for ESA ground data systems and to devise a roadmap for evolution of the current virtualised IT infrastructure of the European Space Operation Centre to a private Cloud, as illustrated in Figure 4

Virtualisation techniques are being more and more utilised at the European Space Operation Centre in the recent years, as the advantages are recognised and appreciated by all stakeholders. The first ESOC virtualised ICT infrastructure was established based on the VMware [Ref. 3] technology mainly in support of development and integration of ground data systems. In the recent years however virtualised ICT infrastructure is also deployed in the operational environments.

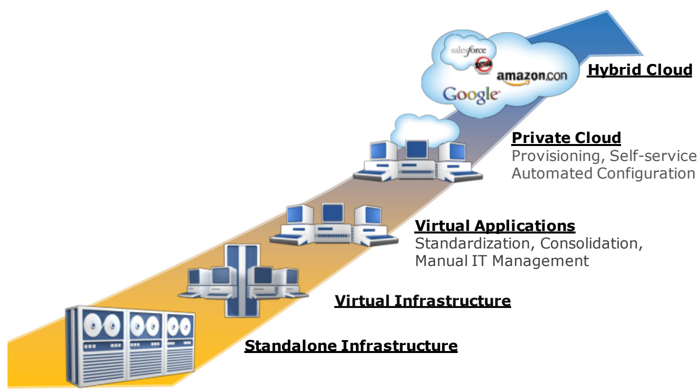


Figure 4. IT Infrastructure evolution.

The provisioning of the virtual computing resources (mainly in form of centrally managed virtual machines) is currently managed by human actors and through manual procedures. A typical scenario is when the customer requests a new virtual machine by filling in a paper form, indicating the level of the required hardware, storage and network resources and sending it, often via email, to the responsible organisational unit in the Agency, So called software baselines must also be selected from a predefined catalogue in the request form, which specify the version of the Operating System, the additionally required packages and third party products (e.g. databases). To ease the process a limited number of standardised "templates" have been defined for development and runtime environments of major ESA ground data systems. The request form goes then through an approval cycle. Upon approval, an ICT engineer creates manually the virtual machines with the basic operating system and configures the network. For this purpose the ICT engineer must interact with a number of different configuration management and ICT service provisioning tools. After the creation and successful deployment of the VM, the ICT engineer must log into the newly created machine and install all required add-ons. The requester is then provided via email with access details, after all installations are validated by the ICT engineer.

This simple scenario reveals the level of manual steps currently involved in a basic provisioning of a virtual machine for development or operational deployment of any component of ground data systems according to Figure 5. Many ground data systems for ESA missions are based on the customisation of generic-purpose and multi-mission software infrastructure (e.g. SCOS2000 [Ref. 4] and SIMULUS [Ref. 5] infrastructures). The deployment and configuration of the various components of multi-mission infrastructure in the provided development virtual machine is also a manual activity performed by ground data system engineers. And last but not least the deployment of the customised ground data systems of a mission in the operational environment is currently equally a manual process. One of the major challenges of all the above provisioning scenarios is the configuration control and management of the ever-growing number of baselines and templates for all involved operating system, packages, libraries, third party products and ground data systems infrastructure components.

The study has analysed the current business processes of the above described provisioning scenarios, the existing interfaces between different organisational units at ESOC, the used configuration and baseline management tools at each provisioning level, the adopted recharging policies within the Agency and the validation concepts in each step of the customer-supplier chain. The result of the analysis is a detailed roadmap towards a more agile provisioning concept based on the Cloud Computing paradigm with a private Cloud deployment model.

The envisioned setup considers the same components and organisational interfaces listed in the as-is analysis, but recommends adoption of modern provisioning and Cloud management tools for streamlining and automating the end-to-end provisioning process. In particular it utilises modern build and configuration management systems (such as like Chef [Ref. 6], Puppet [Ref. 7] or Cfengine [Ref. 8]) which allow the dynamic creation of custom templates by each user and facilitate the automation of the installation and provisioning process for the related software products, towards a roadmap as stated in Figure 4

With regard to the reuse of the components of the generic ESA ground data systems infrastructure, the provisioning of the applications, identified as candidate Platform as a Service (PaaS) and Software-as-a-service (SaaS), is further integrated in the envisaged end-to-end provisioning concept.

V. Evaluation of Cloud provisioning solutions and deployment of Proof-of-Concept demonstrator

The first step in the evolution roadmap towards a private Cloud is the enhancement of the ESOC virtualised environment with a Cloud management layer. The main element of the Cloud management layer is a provisioning tool, which handles the dynamic instantiation of computing and storage resources for users and provides the needed interfaces (APIs) for automation. In the simple scenario of previous section the request for a virtual machine with 1 CPU and a x GB of RAM is not sent in a request form to a human actor. The user interacts instead directly with the Cloud Provisioning layer which utilises the exposed hypervisor interfaces (API) at virtualisation level to instantiate the virtual machine. In the real-world scenario the Cloud provisioning layer is furnished with a large number of more advanced capabilities for managing virtual machine images (or templates), Provisioning of IP addresses and network configuration and injection of further user configurations into the on-the-fly created virtual machine.

For this purpose an evaluation of open source and commercial Cloud provisioning solutions compatible with the virtualised infrastructure at ESOC have been performed as part of the study, which identified the following tools as a result of pre-assessment:

- OpenStack [Ref. 9]
- OpenNebula [Ref. 10]
- Eucalyptus [Ref. 11]
- VMware vCloud™ [Ref. 12]

All tools have similar functional capabilities. The more detailed evaluation has been performed using 24 criteria, such as level of integration with the current ESOC infrastructure, security metrics, standards support, user base, enterprise support model for operational use. The evolution scored among the three open-source solutions the OpenNebula solution slightly higher than the OpenStack followed by the Eucalyputs with a larger gap to both other open source solutions. On the commercial products side,

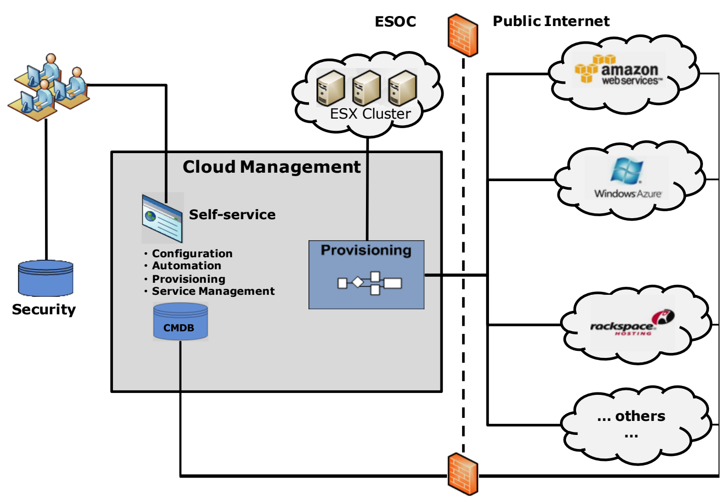


Figure 5. Assessment approach.

the VMWare vCloud™ is particularly attractive due to the fact that current ESOC virtualised environment is based on the virtualisation solutions of the same vendor.

The envisaged concept of enhancing the existing in-house virtualised environment (VMware ESX 4.1) with a Cloud management layer, using the proposed OpenNebula Cloud provisioning solution was successfully demonstrated during the study, using a simplified Proof-of-Concept PoC deployment which supported the following 8 use case scenarios:

1. Dynamic provisioning of virtual machines, using command line
2. De-provisioning of virtual machines using command line
3. Dynamic provisioning of virtual machine using web-based graphical user interface
4. De-provisioning of virtual machine using web-based graphical user interface
5. Import of new virtual machine using command line
6. Definition of application stack (web application) with a set of virtual machines
7. Provisioning of multiple virtual machines as one application stack (web application)
8. Hybrid Cloud setup with public Cloud provider (in this case Amazon) for Cloud bursting

All above listed use-case scenarios could successfully be demonstrated on the PoC deployment. In order to implement the automation required by the use cases 6 and 7 for application, supplementary configuration management tools Chef [Ref. 6] and Puppet[Ref. 7] were adopted.

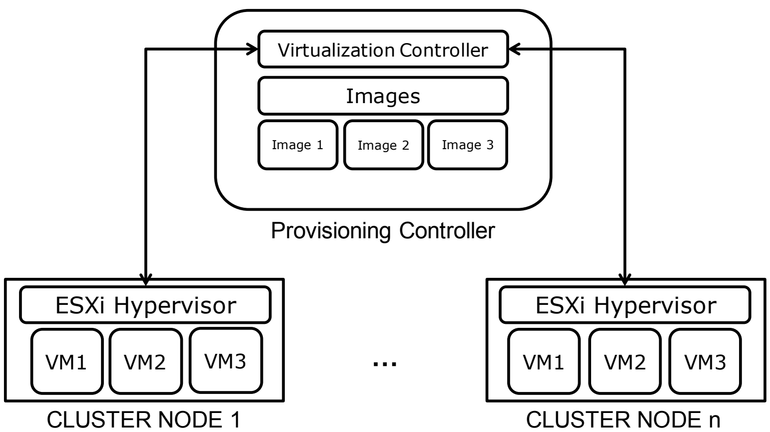
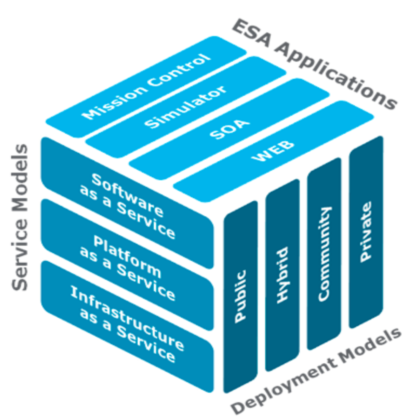


Figure 6. Provisioning architecture

It is worth mentioning that the Commission of the European Communities (Information Society & Media Directorate-General) has published a report in May 2012 about the Advances in Clouds [Ref. 14]. The report mentions specifically OpenStack and OpenNebula, along with technologies as promising technologies to implement the cloud management, especially for IaaS in combination with virtualisation.

VI. Conclusion

Cloud Computing paradigm has the potential for addressing a number of challenges in development, deployment, operation and maintenance of modern ground data systems. The key factor for successful application of this promising paradigm to ground data systems domain is however the identification of the appropriate service provisioning model (IaaS, PaaS, SaaS) and Cloud deployment model (private, community, public, hybrid) for each candidate application.



Not every application is a suitable candidate for moving to the Cloud and even less is every ground data system suitable for moving to a IaaS public cloud solution. It is therefore essential to perform a systematic analysis of the ground data systems application portfolio based on a well-defined set of representative metrics to identify the best candidates for each service and deployment model, according to Figure 6

Private clouds are considered the next natural step in the evolution of many in-house data centres, which have already transitioned from traditional data centres to the virtualisation infrastructure [Ref. 14]. The step from virtualisation to private cloud is not as big as one may imagine. From technical point of view, it is mainly about adding a so-called cloud management layer to the already existing virtualisation layer. A number of capable and promising open source solutions are available for this purpose. The challenges relay more in the organisational aspects and the introduced changes to the existing business processes and internal recharging schemes in every large organisation.

The Cloud Computing Study performed at the European Space Operation Centre has devised a method for performing systematic cloudability analysis of ground data systems of space missions and has identified the suitable applications for each service provisioning and deployment model. It has also specified a concrete transition concept for the ESOC virtualised infrastructure to a private cloud and validated the concept by deploying a Proof-of-Concept private cloud demonstrator.

Appendix A

Acronym List

API	Application Programming Interface
CPU	Central Processing Unit
ESA	European Space Agency
ESOC	European Space Operation Centre
EGOS	ESA Ground Operation System
ESB	Enterprise Service Bus
GB	Giga Bytes
IaaS	Infrastructure as a Service
ICT	Information and Communication Technology
IT	Information Technology
IP	Internet Protocol
NIST	National Institute of Standards and Technology
PaaS	Platform as a Service
RAM	Random Access Memory
SaaS	Software as a Service
SCOS	Spacecraft Operation System
SLA	Service Level Agreement
SOA	Service Oriented Architecture
SSA	Space Situational Awareness
US	United States
VM	Virtual Machine

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