ESTRACK Long Term Load Analysis

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For ESA it is crucial to perform Long Term Load Analysis (LTLA) of its global network of TT&C stations (ESTRACK). The resulting network load forecasts are essential for the management of the ESTRACK network and provide a reliable basis for financial planning. The knowledge of the predicted network load supports the appropriate scaling and timing of maintenance and engineering activities as well as securing the necessary investments to cope with mission requirements. Furthermore the identification of bottlenecks supports the scaling of complementary services from external providers. Moreover, the forecasted network load allows the optimal alignment of resources and eventually future missions designs. With the 2008 introduction of network resource planning presented at previous SpaceOps, ESA laid the ground for Long Term Load Analysis. ESOC developed different scenarios defined by a set of consistent assumptions and variables on the future usage of ESTRACK. The scenarios are simulated by applying the smart network resource planning algorithms on the set of scenario specific parameters such as predicted trajectories and TT&C specifications. This paper elaborates on the required inputs for scenario definitions and discusses the implications and practical challenges of the chosen approach. It illustrates various ways of presenting the resulting data and demonstrates the relevance of the information derived from the interpretation of the data. The paper establishes that LTLA can increase the cost efficiency of ESTRACK and concludes with suggestions on an integrated Long Term Load Analysis process, spanning from mission design to ground Segment Operations to reduce overall costs. Such integrated analysis could be considered a prerequisite for possible inter-network sharing of resources.

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I. Introduction

THE European Space Agency operates and maintains a global network of ground stations (ESTRACK), which comprises several Telemetry, Tracking and Command (TT&C) ground stations. Today the ESTRACK core network encompasses 10 antennas on 9 different sites, as follows:

- Six 15m and one 13m TT&C station (Kiruna - Sweden, Redu - Belgium, Maspalomas & Villafranca - Spain, Kourou - French Guiana, Perth - West Australia;
- Two 35m Deep Space ground stations in New Norcia - Western Australia and in Cebreros - Spain - a 3rd Deep Space ground station is being built in Malargue - Argentina;
- One 5.5m station on the island of Santa Maria, Azores - Portugal for tracking of Ariane/ ATV launches.

This core network is augmented through long term contractual arrangements with commercial tracking service providers. Furthermore, additional non-ESA stations are occasionally used by ESA under cooperative agreements with Partner Space Agencies (ASI, CNES, DLR, JAXA, NASA).

The ESTRACK comprising ground stations from the core network, the augmented network, and the cooperative network is depicted in Figure 1.

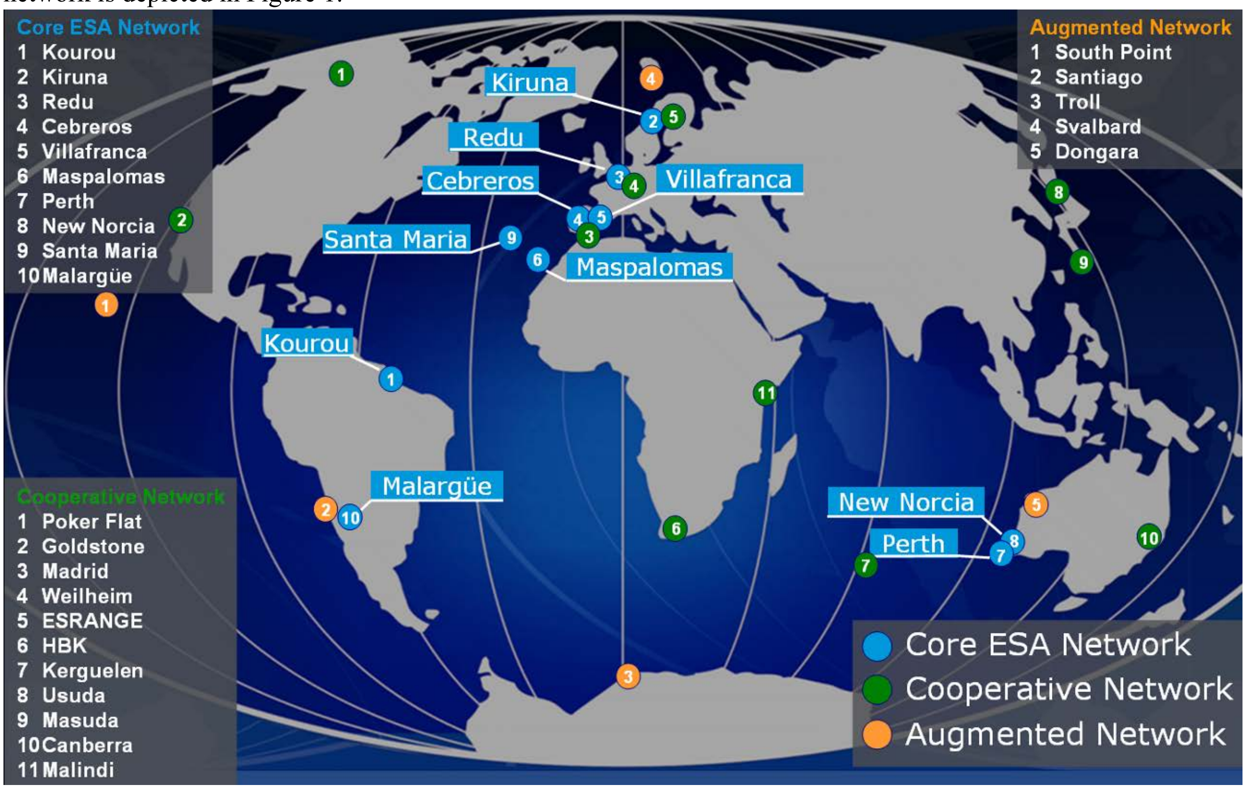

Figure 1. ESTRACK Stations Network

As operator and maintainer of ESTRACK, it is crucial for ESA to predict the future load on ESTRACK as precisely as possible. To this end, ESA has recently introduced a "Long Term Load Analysis" service (LTLA) for ESTRACK. The purpose of the LTLA service is the identification of oversubscription (i.e. conflicts) and the identification of spare capacity within ESTRACK. The identification of oversubscriptions enables

- the validation of the feasibility of operations, infrastructure or maintenance design
- appropriate scaling and timing of maintenance and engineering activities
- appropriate scaling of complementary internal resources
- appropriate scaling of complementary external resources

The time range covered by LTLA is flexible. It starts ~18months[5] for Deep Space assets (3months[6] for stations dedicated to support of Low Earth Orbiting (LEO) spacecraft) in the future and covers a period of multiple years as required and feasible[7]. The scope of LTLA comprises the ESTRACK Core Network (or an appropriate subset) and the missions using those assets. Augmented and Cooperative terminals may be included to estimate the volume of required external services. The resulting ESTRACK load forecasts are essential for the management of the ESTRACK and provide for a reliable basis for financial planning.

II. The traditional LTLA approach

As the knowledge of future oversubscription and space capacity has always been of interest to the managers of ESTRACK, a number of approaches were applied in the past to obtain such understanding.

- A popular approach involved a commercial COTS software suite, which enabled the users to visualize and analyze space/ground contact periods. Such analysis was customarily performed on a simple scenario (e.g. considering only a single station and few missions using reference orbits). This approach enabled a statistical analysis of the scenario, including the number of conflicts.
- A further approach was based on a set of assumptions regarding the support availability of a station. This approach was applied especially for the case of ESA's Kiruna ground station in Sweden, as this ground station comprises two antennae, which are dedicated to the support of Low Earth orbiting (LEO) satellites. The approach assumed that – on average – a LEO satellite orbit has a duration of ~100 minutes, leading to a maximum of ~14.4 orbits a day. As each antenna can support a maximum of three contacts per 100 minute period, a maximum of 86.4 contacts could be realized on a daily basis using both antennae and assuming spacecraft's in perfectly synched orbits. Knowing that the antennae require downtime and safety margins in their load, it was assumed that a maximum of 70% of those 86.4 contacts should be considered the theoretical maximum of the station. Comparing the number of contacts available with the amount of contact required during a period, enabled a statistical analysis comprising the number and volume of conflicts.

An example of such a traditional LTLA output is shown in Figure 2.

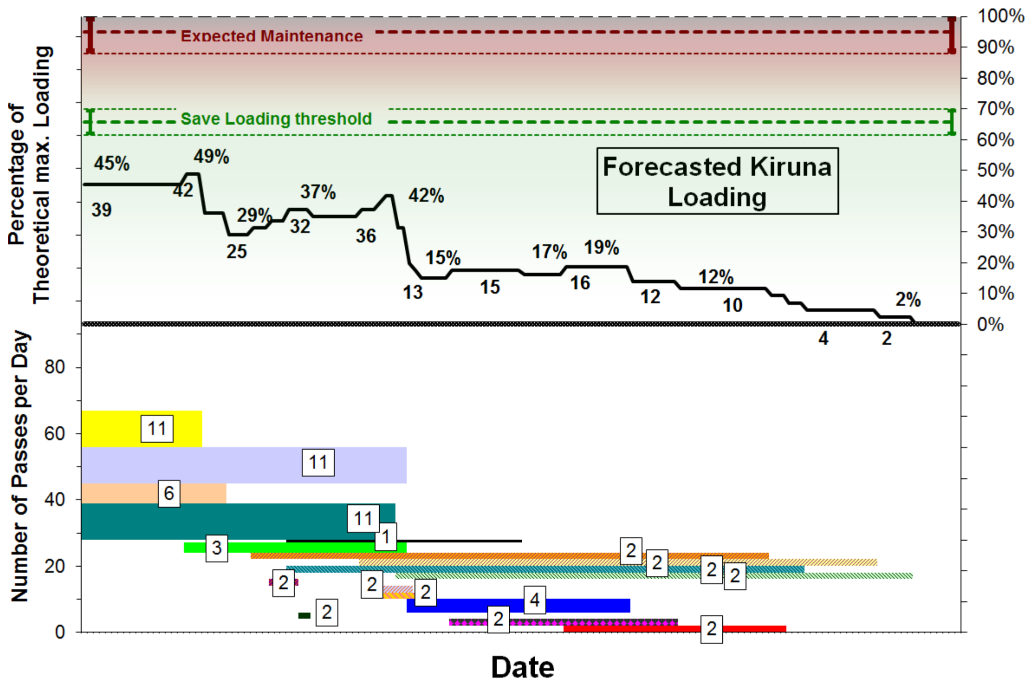

Figure 2. Traditional Kiruna LTLA output

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[5] the current nominal planning cycle for Deep Space assets covers up to 18 months
[6] the current nominal planning cycle for LEO dedicated terminals is up to 12 weeks
[7] limitations could e.g. be introduced by the availability of orbits/trajectories and/or support requirements

Common to both approaches is the quantitatively-focused analysis. The approaches provided statistical information, including indications on the amount and volume of conflicts over a period. This approach allowed an assessment whether the resources available are sufficient on average. Detailed qualitative information in the topology of the conflicts (e.g. the maximum/average amount and volume of consecutive passes which meet the conflict criteria) and exact information on the required complementary resources were not available.

III. Recent changes in ESTRACK Planning enabling LTLA

The traditional process for conflict-free planning of ESTRACK services was implemented at a time of comparatively low resource utilization, complexity and computerization standards. As the complexity of the process grew significantly over time due to increased ESTRACK utilization and increasingly complex utilization requirements of ESTRACK customers ESA automated the planning of ESTRACK services with the specification, development, and deployment of the ESTRACK Management System (EMS), more specifically its planning component the ESTRACK Planning System (EPS)[i]. The introduction of the EPS into the ESTRACK planning process, facilitated the implementation of a largely automated planning process, which

- ensured conflict free planning of ESTRACK services
- respected all service requirements, constraints and preferences of all ESTRACK customers
- provided efficient, centralized and time-saving conflict solving mechanisms
- provided transparency, clarity, predictability and reproducibility to ESTRACK customers

The current planning horizon covers a period of committed ESTRACK services between 7 and 13 months ahead for Deep Space assets. This committed plan is complemented with a non-committing preview covering up to 18 months.

To cover such range the EPS, which was initially designed to only plan three weeks ahead, underwent major technical evolution. As the complexity of conflict-solving algorithms increase exponentially with the time range to be processed, planning 18 months in a single attempt was not feasible. To evade this limitation, the processing of longer periods is done incrementally on shorter periods, each overlapping partially with the previous and following period (see Fig.3). The choice of an appropriate incremental period is difficult and requires smart management of the boundary conditions at the overlaps of two adjacent incremental periods. The incremental planning approach enables planning of longer periods, while ensuring linearizing and thereby limiting the processing time. Planning performed following this approach is thus no longer limited by processing time, but rather by the availability and accuracy of orbital predictions.

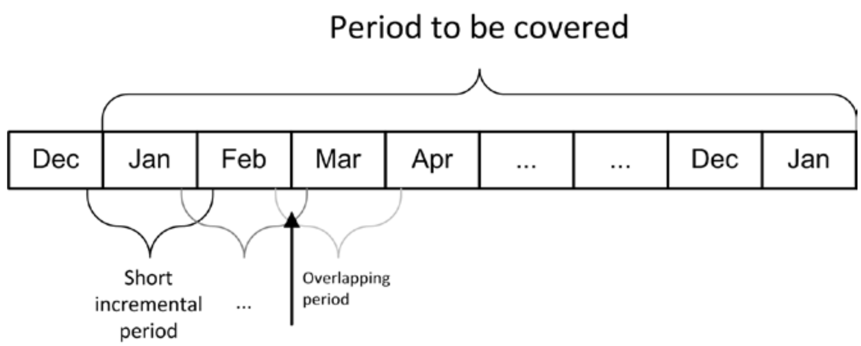


Figure 3. Incremental approach to planning of longer periods

IV. ESTRACK Long Term Load Analysis

The evolution of the EPS to cover longer planning periods provided ESA with the opportunity to perform a more detailed quantitative and qualitative Long Term Load Analysis by re-using the same basic concepts and tools used for short and medium term planning. The advantage of the EPS based LTLA are multifaceted; The most important is the ability to exactly identify the type of conflicts and the resources required to provide the services on a case-by-case bases rather than merely on a averaged statistical basis.

The knowledge of the predicted network load provides ESA with accurate and detailed requirements as well as sufficient lead time to secure additional resources. It furthermore enables appropriate scaling of maintenance and engineering activities as well as necessary investments to cope with mission requirements. Moreover, the forecasted network load allows the optimal alignment of resources and eventually future missions designs.

A. Re-use of the EPS – Advantages and Issues

Variables defined by recent LTLA requesters show a trend towards increasingly complex requirements. Whereas traditionally driven by physical limitations such as spacecraft visibility, recent requirements are increasingly driven by technical concerns (e.g. only parts of the orbits can be used for contacts) or financial concerns (support shall be provided during working hours or within only one shift of Spacecraft Controllers). These constraints significantly restrict the potential solutions and increase the likelihood of conflicts. The EPS with its ability to handle complex scenarios is uniquely equipped to incorporate such requirements and to provide a LTLA service.

In addition, the re-utilization of an operational tool for LTLA services has the advantage that any analysis is based on an operationally valid solution. Whereas traditional approaches to LTLA failed to consider complex requirements and were potentially based on operationally invalid scenarios, the use of the EPS ensures full compliance. Moreover the application of the same basic concepts and tools used for operational planning enables a smooth transition of LTLA to operational planning, as the configuration for both purposes is maintained within the same application.

However, as the ESTRACK Planning System (EPS) was originally not designed for LTLA purposes but for operational short- and medium-term planning of ESTRACK, the systems did not allow for conflicts, but rather tried to resolve conflicts where possible or aborted the allocation of contacts due to insufficient TT&C resources.

In order to allow persistent conflicts, the notion of virtual ground station has been introduced. Virtual ground stations are virtual clones of physical ground stations. In case the physical ground stations cannot accommodate the mission, it is moved to the virtual ground station. The resulting load of the virtual station enables the simple and efficient identification of locations and times based on the user's preference where and when additional complementary resources are required and thus drives the decision to buy or to build resources in the vicinity. Potential external TT&C service providers are included into the analysis in order to enable the identification of external TT&C services with exact information as to the volume and time. This does however not constitute a commitment of either side. The information is used for the timely scaling of contracts and requesting of services.

B. Input Parameters and Handling of Uncertainty

Long Term Load Analysis is applied on scenarios. Scenarios are a set of parameters comprising boundary conditions, variables and assumptions. The boundary conditions comprise terminals, missions, the time-frame and the trajectories / orbits of the selected missions. The variables comprise:

- The required TT&C volume (e.g. minimum volume, maximum volume, full visibility at a single station, maximum coverage from multiple stations);
- The valid visibility (e.g. an event based specification during which parts of the orbit support shall be provided (e.g. support during apogee of the spacecraft, support during nominal working hours of the Spacecraft Control Centre, support after each "blind orbit", etc.);
- The desired distance between two successive contact periods (e.g. no less than 6 hours between two contacts, e.g. no more than 3 orbits without contact);
- Requirements regarding the handover of support from one ground station to another ground Statin in mid support (e.g. no more than one handover per contact);
- Support preferences across stations (use ground station X whenever possible instead of ground station Y) and
- Inter-spacecraft constraints in case of multi-spacecraft missions (e.g. to ensure comparable support volumes for Spacecraft-1 and Spacecraft 2).

Finally the assumptions applied to the scenario comprise – inter alia – the launch dates, extensions and termination dates of potential ESTRACK users within the specified time frame and the evolution of ESTRACK, such as assumed closures or additions of ground stations.

The (lack of) accuracy of orbital information is a common source of uncertainty. For missions with limited orbit propagation abilities such as some LEO satellites in a polar orbit, an exemplary, representative period may be planned and statistically analyzed, as the exact time range is not important. By planning a sufficiently long time range[8] a valid statistical representation can be derived. This statistical approach provides an estimation of the maximum-, average-, minimum-, and standard deviation of the amount of conflicts and detailed information on the topology of conflict and thereby allows to infer the service volume to be procured externally. For a deep space mission orbital prediction accuracy is not as much of an issue, as the orbit of the target (usually a planet) is known years in advance. The influence of the launch date is thus small for what concerns LTLA.

[8] typically 6 to 12 months for LEO-type spacecraft

Another common source of uncertainty are the variables included into the scenario. missions in early preparation states may initiate the first LTLA with very basic requirements only. As the mission's design evolves, the variables specifying the support characteristics concretize and the LTLA is updated in an iterative approach.

The uncertainty of the variables is managed by two mechanisms. Firstly the input parameters are carefully selected to ensure that the most-likely scenario is used as baseline, while avoiding over-specification; Secondly the analysis is performed multiple times with changing variables, thereby determining the likely solution space of the analysis.

In order to achieve a stable LTLA service with comparable outputs a regular LTLA service has been established in the mission Operations Department in ESA's Directorate of Human Spaceflight and Operations. This baseline scenario, comprising the most-likely parameters, is updated annually and approved by the Head of Operations. This baseline scenario is the starting point of all event-driven LTLA activities, which may adapt, complement or replace the baseline parameters as appropriate.

C. Data Presentation

The output of the LTLA planning process is a station allocation plan identifying each individual contact period per mission for the complete time period. The data is subjected to further treatment and transferred to an open-source eclipse-based Business Intelligence and Reporting Tool, which provides plotting capabilities and derives consolidated statistical information. The range of outputs spans from tabular statistics to spacecraft visibility plots, GANTT charts and histograms as shown in below examples [Fig. 4-10].

Depending on the leading question a particular representation of the data may be advantageous over others. A highly useful tool are plots illustrates the geometric access (i.e. possible contact periods). Visualizing the individual geometric assesses at a ground station by spacecraft (Fig. 4) or the geometric assess of particular spacecraft over multiple ground stations (Fig. 5) enables a first estimation of possible peak periods. Such plots highlight at first glance the maximum contact duration (in case of Figure 4 approximately 19 hours) a spacecraft may expect from a set of ground stations and the overlap of the geometric access of these ground stations (approximately 2 hours). Similarly Figure 5 highlights the overlap of geometric access to multiple spacecraft from a single ground station and illustrates that as many as four different spacecraft may demand the same ground station at the same time, thereby indicating a large potential for conflicting requests.

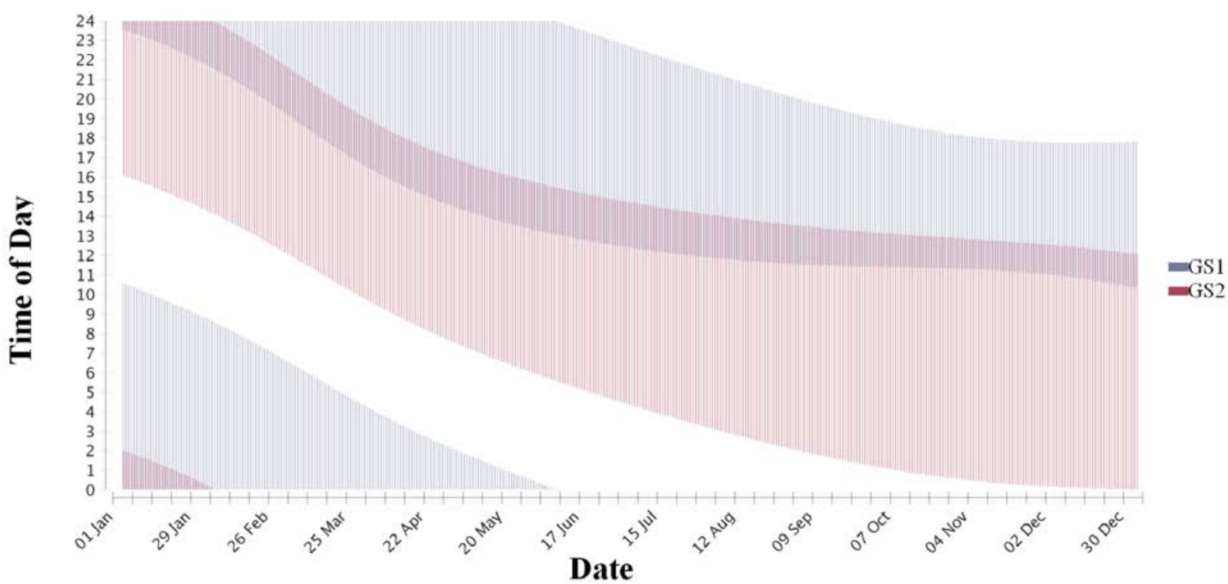


Figure 4. Possible contact periods per spacecraft and ground station

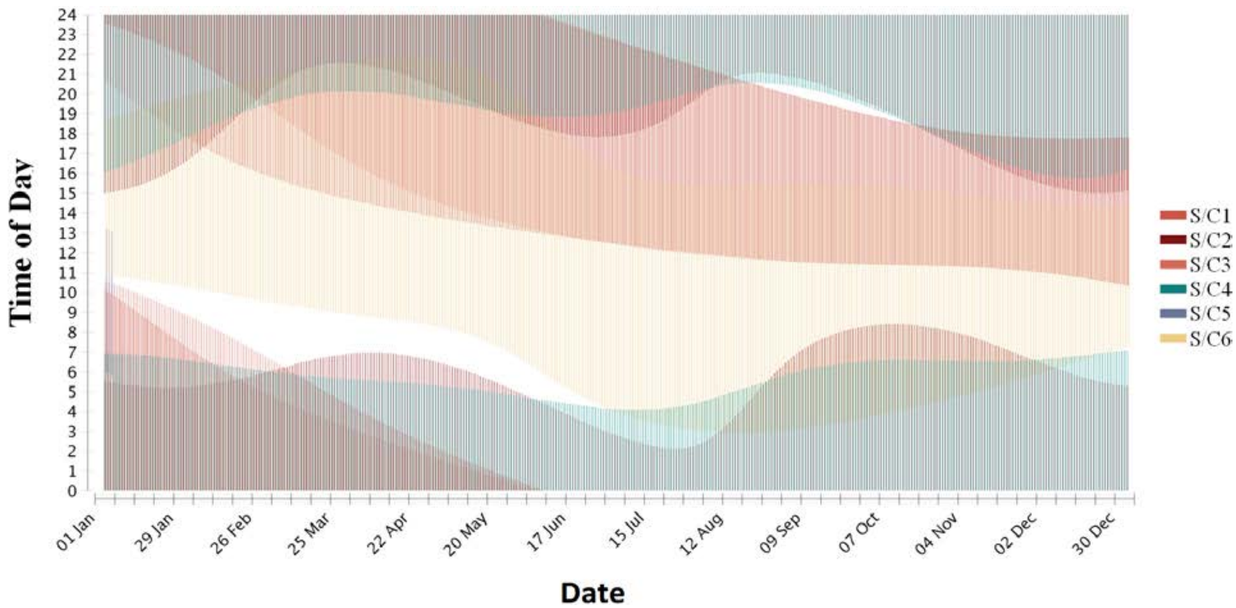


Figure 5. Possible contact periods per ground station and spacecraft

While above outputs show possible contact periods, it is also possible to provide a plot of the actually allocated contact periods. Figure 6 provides an examples of a graphical representation of the conflict-free contacts committed at a single ground station by spacecraft, while Figure 7 provides a view of the contact times committed to a particular spacecraft per ground station. Such representations of the data are useful for missions to visualize the estimated service and is thus especially suitable for plausibility and consistency checks, as the pattern of the contact allocation is immediately visible. Such information is often as interim output in iterative LTLAs performed for missions in preparation, as the impact of refined variables is immediately recognizable in the plot.

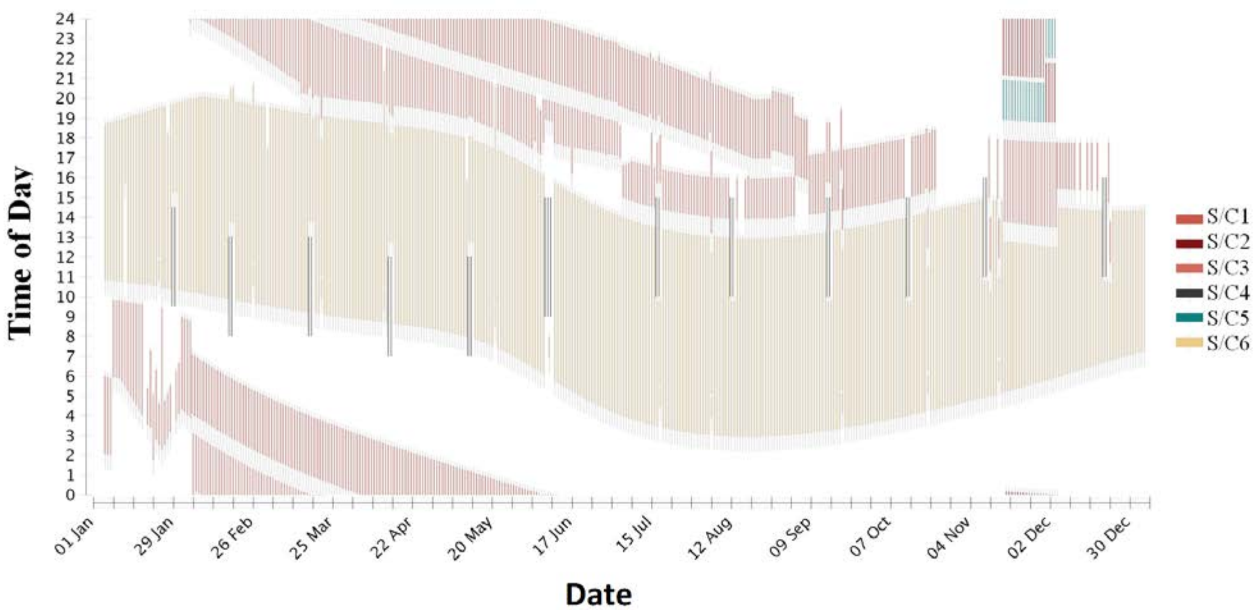


Figure 6. Parameterized plot illustrating the contacts per ground station and spacecraft

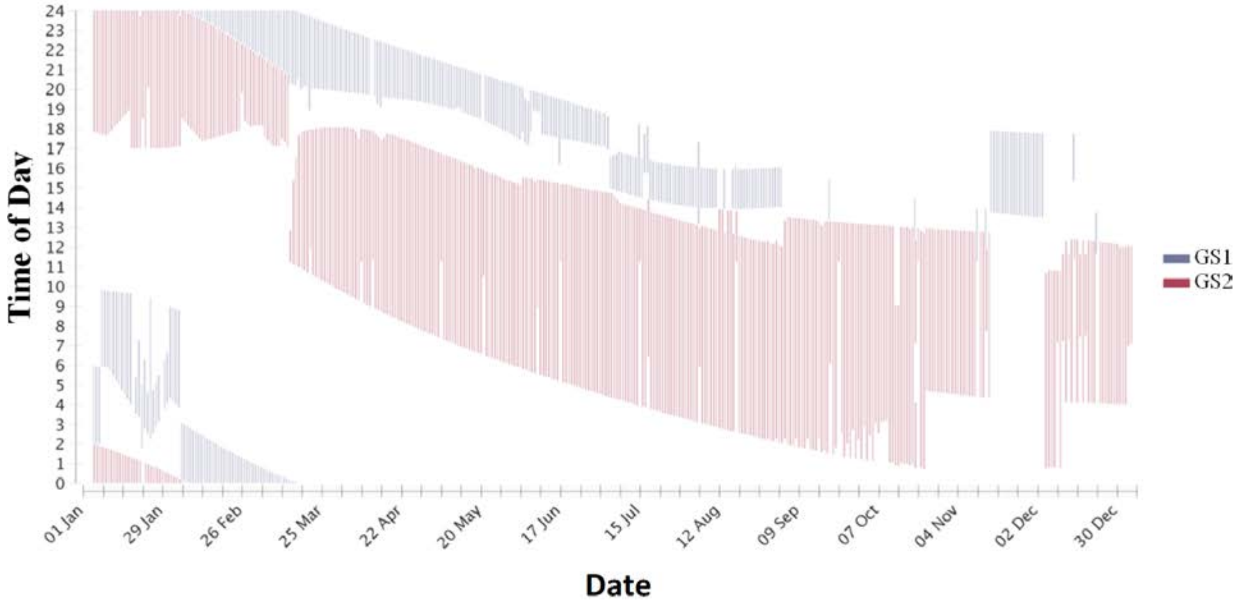


Figure 7. Parameterized plot illustrating the contacts per spacecraft and ground station

In order to identify the exact number of contacts and/or duration of contacts per spacecraft and ground station a tabular presentation is usually preferred. While Figure 8 is commonly more useful for LEO-type missions, Figure 9 is more suitable for Lagrange-point or Deep Space missions.

Ground Station	Total Number of passes (complete range)	Average per Quarter (4.01 Quarters)	Standard Deviation per Quarter (4.01 Quarters)	Maximal Number of Passes per Quarter	Minimal Number of Passes per Quarter	Average per Month (12.03 Months)	Standard Deviation per Month (12.03 Months)	Maximal Number of Passes per Month	Minimal Number of Passes per Month	Average per Day (366 Days)	Standard Deviation per Day (366 Days)	Maximal Number of Passes per Day	Minimal Number of Passes per Day
Total	608												
CEB	261	65.072	27.032	90	24	21.691	12.061	31	1	0.713	0.259	2	1
NNO	347	86.513	7.942	92	73	28.838	9.855	32	1	0.948	0.075	2	1

Minimum and maximum numbers take only days resp. months and quarters into account where there was at least one service.

Figure 8. Tabular presentation of the number of contacts by ground station

Ground Station	Total Duration (complete range)	Average per Quarter (4.01 Quarters)	Standard Deviation per Quarter (4.01 Quarters)	Maximal Duration per Quarter	Minimal Duration per Quarter	Average per Month (12.03 Months)	Standard Deviation per Month (12.03 Months)	Maximal Duration per Month	Minimal Duration per Month	Average per Day (366 Days)	Standard Deviation per Day (366 Days)	Maximal Duration per Day	Minimal Duration per Day
Total	3671:02:40												
CEB	720:53:20	179:43:47	83:41:31	306:20:50	91:04:20	59:54:35	37:27:53	117:41:37	02:00:00	01:58:10	01:04:20	08:08:51	01:00:00
NNO	2950:09:19	735:31:25	156:01:19	935:49:42	566:02:26	245:10:28	99:08:09	329:12:52	08:05:57	08:03:37	02:15:41	12:00:00	01:00:56

Minimum and maximum numbers take only days resp. months and quarters into account where there was at least one service.

Figure 9. Tabular presentation of the duration of contacts by ground station

The tabular presentations comprise the standard deviation, the total, the maximum, the minimum and the average number of contacts and contact duration per day (or custom period) as well as the number of days (or custom period) without contacts. Such presentation is beneficial when trying to estimate the possible contact volume from internal ground stations as well as the required volume of complementing external resources. Figure 10 provides a complementing graphical presentation of the contact duration per spacecraft and ground station. Such charts are convenient to perform plausibility checks on the data.

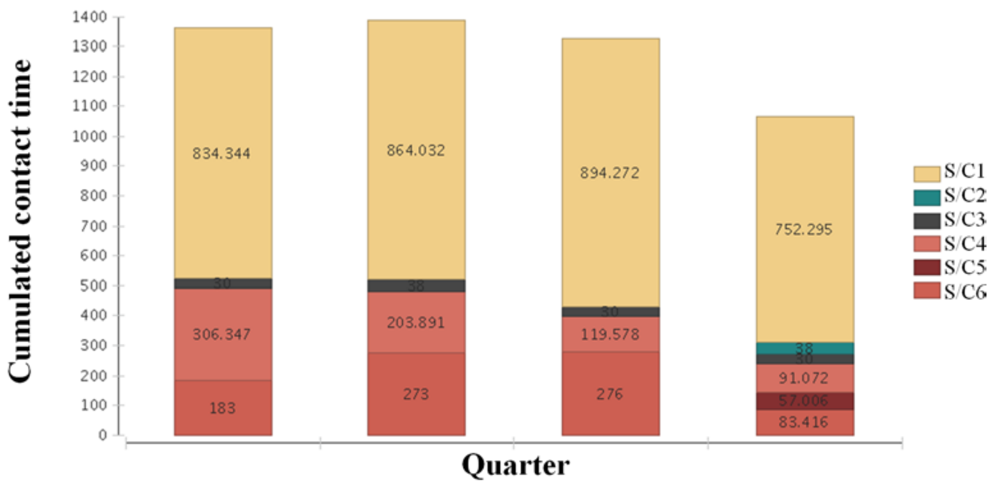
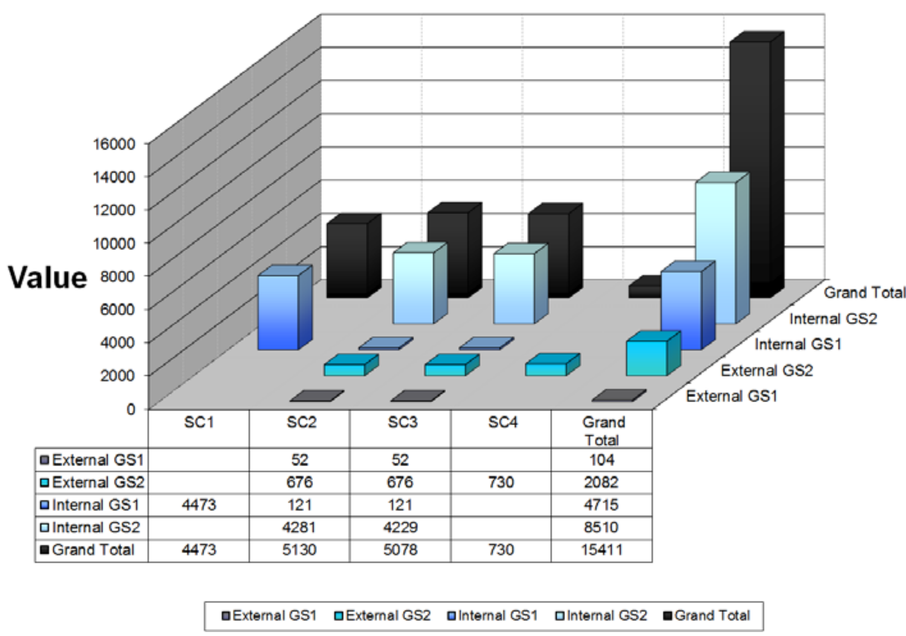


Figure 10. Illustration of contact duration per ground station and spacecraft on a quarterly basis

D. Significance and Practical Application

The data derived from the LTLA performed for ESTRACK have proven beneficial in many different contexts.

A LTLA was performed in 2010 covering the LEO-support dedicated antennae of ESTRACK in the time-frame 2011 to mid of 2012. The analysis was performed on representative reference orbits and the resulting data was statistically assessed and presented in a tabular form (see Fig. 11). The LTLA helped assessing the impact of orbit evolution beyond the projected lifetimes of ERS-2 and ENVISAT and provided details on the likely interference as their orbits were getting out of sync. The accuracy of the forecasted complementary service volume required from



	SC1	SC2	SC3	SC4	Grand Total
External GS1		52	52		104
External GS2		676	676	730	2082
Internal GS1	4473	121	121		4715
Internal GS2		4281	4229		8510
Grand Total	4473	5130	5078	730	15411

Figure 11. Tabular form identifying the support volume for four different spacecraft from two internal and two external ground stations

external ground stations was >95%. The ability to predict the requirements so accurately resulted in more meaningful requests with longer lead-times to the augmented network partners and thus on average in a higher availability. The analysis furthermore supported the identification of the optimal slot for a major maintenance activity required at one of the terminals. The maintenance peak was aligned with the minimum of the load.

A more recent LTLA performed on the LEO-support dedicated antennae of ESTRACK helped in the assessment of future LEO mission's costs, as loading and capacity of internal resources were known and the volume of complementary resources could be easily identified. This enabled a more accurate financial planning than it would have been possible previously. Such information is valuable feedback for missions still in design phase, as the optimal alignment of spacecraft design and ESTRACK capabilities and capacity can be targeted.

Another LTLA was performed in 2011 on ESA's 15 meter network covering the time-frame 2013-2018. The analysis was performed on long term orbit propagations and the resulting data was statistically. The LTLA was used in the discussions regarding the potential closure of a ground station. It helped assessing the potential impact on customer missions of removing a ground station from ESTRACK, by concretizing the volume that could successfully be transferred to other ESTRACK stations or to augmented network partners and the volume that would be lost to the mission. The assessment of the involved costs and loss of contact period for the mission provided the bases for the classical make or buy decision.

A more recent LTLA was performed on ESA's Deep Space assets in the time-frame 2015-2020. The analysis was performed on long term orbit propagations and the resulting data was statistically evaluated. The LTLA provided ESA with detailed and reliable forecasts of the loading of ESA's Deep Space assets, highlighted periods of particularly high load and thereby provided the basis for decision on investments in e.g. MSPA (Multiple Spacecraft per Aperture) capabilities and new ground stations.

These are just a couple of examples of the significance and value of the data derived from LTLA. Common to all LTLA applications is the benefit of knowing in advance the load of the network, the volume and characteristics of complementary services to be procured and the volume and characteristics of spare capacity. This provides the basis for reliable long term financial planning and leads to optimization of resource usage and thus to cost efficiency.

The increased planning security resulting from systematic application of LTLA and the consequential accurate and detailed forecasts of spare capacity could be used to specifically approach prospective customers. LTLA enables an accurate assessment of a mission's requirements in the long term and allows for realistic cost estimations for the provision of TT&C services. LTLA may indeed become a very handy tool, supporting the technical and financial design of new missions and may even become a prerequisite for possible inter-network sharing of resources.

V. Conclusion and Outlook

This paper reported on the implementation of a Long Term Load Analysis service within the European Space Agency for the agency's global network of TT&C stations (ESTRACK). The implementation of the service draws on recent changes in the operational planning of ESTRACK, enabled by the ESTRACK Management System (EMS). The re-use of concepts and systems applied in the operational planning enables the analysis of complex scenarios reflecting all of the mission's requirements and preferences, ensures consistency of the LTLA with actual operational planning and facilitates a seamless transition from LTLA to operational planning.

The technical implementation, allowing for the planning of long periods with limited processing capacities was challenging, but benefited greatly from extensive experience already gained in operations. The uncertainty introduced by the lack of accuracy of orbital information was less pronounced than expected as for LEO-type orbits a statistically significant period can be analyzed with reference orbits, while the orbital information for Lagrange-point, Deep-Space or highly-elliptical orbits is anyhow high and the delta introduced by changing launch dates is typically limited to a short period of time.

The paper demonstrated the practical application of the LTLA and the significance of the resulting data for ESA. LTLA enables ESA to reliably predict and commit to services far in the future, based on customer specified parameters. It supports financial planning, the classical "make-or-buy" decision, scaling and timing of contracts and the maintenance strategy for the network.

This paper concluded that the LTLA could further be of use for enabling cost-optimized alignment of the ground network and prospective missions as well as possible future inter-network sharing of resources.

Appendix A
Acronym List

ASI	Agenzia Spaziale Italiana (Italian National Space Agency)
ATV	Automated Transfer Vehicle
CNES	Centre National Etude Spatial (French National Space Agency)
COTS	Commercial of the Shelf (equipment)
DLR	Deutsche (Forschungsanstalt für)Luft- und Raumfahrt (German National Space Agency)
EMS	ESTRACK Management System
ENVISAT	Environmental Satellite
EPS	ESTRACK Planning System, an EMS system
ERS-2	European Remote Sensing Satellite, 2^{nd} Generation
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTRACK	European Space Tracking Network
GS	Ground station
JAXA	Japan Aerospace Exploration Agency (Japanese National Space Agency)
LEO	Low Earth Orbit
LTLA	Long Term Load Analysis
NASA	National Aeronautics and Space Administration (US National Space Agency)
SC	Spacecraft
TT&C	Telemetry, Tracking and Command

Appendix B

Glossary

15 meter Network	Subset of ESTRACK comprising antennae with a dish size of 15 meters
ESTRACK	A network of ground stations and communication equipment
ESTRACK Augmented Network	Network of TT&C ground stations available to ESA through long term contractual arrangements with commercial tracking service providers
ESTRACK Cooperative Network	Network of TT&C ground stations available to ESA under cooperative agreements with Partner Space Agencies
ESTRACK Core Network	ESA owned global network of TT&C ground stations

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