ICAS-92-2.3.2

CONTRASTING FACTORS IN THE DESIGN SPECIFICATION AND VERIFICATION OF AIRCRAFT AND SPACECRAFT SYSTEMS

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Abstract

This paper examines satellite payloads and avionic systems in order to identify the reasons for differences in the design, integration and testing used. Future applications demand changing considerations and the techniques of one discipline may become increasingly appropriate to the other. Payloads on remote sensing satellites are featured as the complexity of the geophysical parameter retrieval particularly emphasises these differences. The principles however, are broadly applicable.

The spacecraft specification and design process including calibration, characterisation and verification aspects is shown to be particularly complex due to the ill-definition of the geophysical/engineering parameters relationships. Further contracts and possible areas of cross-discipline application involved in the implementaion interpretation and testing of systems are also covered.

The possible use of a system performance model to optimise payload specification as in avionic methodolgy is discussed. Initial results using such a model for a microwave radiometer are described.

1. Introduction

1.1 Scope

This paper identifies the differences between the design specification and implementation methodologies of aircraft and spacecraft. As the functional and performance requirements of spacecraft become more demanding, and avionic systems have to be developed on shorter timescales, one discipline may be able to use more of the techniques developed by the other. This is the rationale behind the research at the University of Southampton which is investigating the optimisation of spacecraft payload design using established avionic principles.

1.2 Technical Background

To illustrate the critical areas in satellite payload definition the process of defining remote sensing satellite payloads will be described. These payloads observe, under particular pre-defined conditions (geometry, frequency, polarisation etc), a scene that will vary within well known limits. Received energy and the small changes observed between channels, allows a number of geophysical parameters to be estimated.

A diverse set of users have requirements on products that are derived from a particular satellite's payload. These geophysical parameters (eg rainfall rate) are derived by processing the raw data (which is the radiated or reflected energy at the frequency of interest). To obtain each geophysical parameter, retrieval algorithms are derived from relationships derived analytically or empirically. Exact and complete relationships of the process linking the satellite observation and the retrieved parameter do not exist and the optimal algorithms may only be established post-launch subsequent to a ground truth measurement campaign.

The technical specification of the spacecraft system is in terms of engineering parameters (eg channel frequency, antenna diameter). There exist complex interactions and dependancies between these parameters and geophysical parameters. The optimum design trade-off to meet the geophysical specification is therefore difficult to establish.

An aircraft avionic system end user, on the other hand, has specific requirements in terms of the performance of the avionic system. This can be measured by specifing the physical properties or capabilities of the aircraft (such as the error in the navigation system or the accuracy of delivering weapons). The avionic system, however, must cover the extensive range of operation and functional moding options that exist.

2. Spacecraft

2.1 Specification and Design

The process of specification, design and implementation for a spacecraft system is illustrated in Figs 1 and 2. This shows the design factors linking the user requirements and the engineering parameters. Each component of the design process is reviewed and compared to the avionic equivalent in the following sections.

2.2 User Requirements

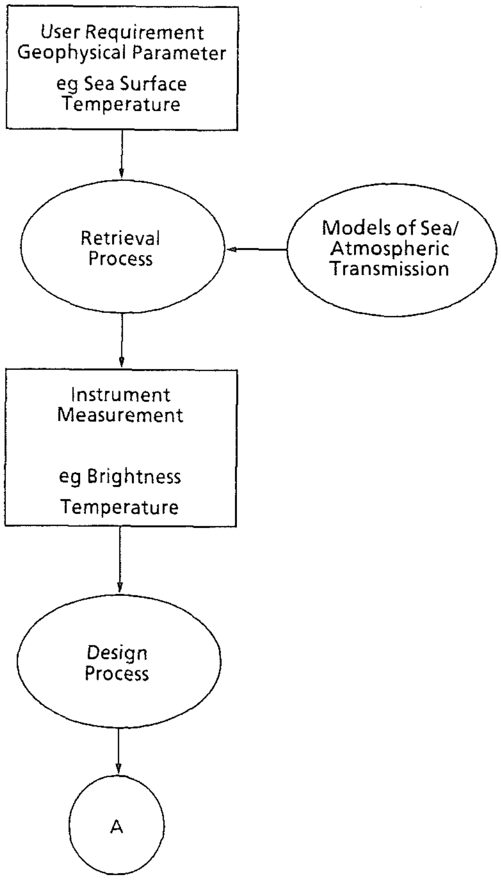
The specification of a spacecraft payload is made at two levels. The user requirements are usually specified in geophysical terms, and then the engineeering parameters which relate directly to the instrument design are derived.

Fig 3 illustrates the complexities involved in the transition from the user requirements to the definition of the design specification. A number of factors external to the system and numerous interactions within the system, lead to critical areas in the definition of user requirements. The most critical areas in the resolution of a particular payload's user requirements are:-

- precise specification of definitive user requirements in terms of geophysical parameters is often not possible due to the diverse applications that exist.
- Data quality and familiarity of form, timeliness of the processed product and synergistic use ie its compatability with other satellite or ground-based data are important factors in determining product usefulness.

- Currently available user models of the geophysical events being observed determine specific product requirements in terms of accuracy and scale.
- These models also play a role in the development of inverse algorithms for the retrieval of the geophysical parameters from the raw satellite data. This involves a comparison of instrument measurements with an extensive post launch ground campaign. The accuracy and scales over which the ground comparison and calibration campaign are possible, therefore, indirectly determine the limits of performance requirements.
- Conflict between parameters for the optimal instrument baseline design are considered on a case by case basis, due to the complexity of the interactions and the uncertainties in establishing instrument design sensitivities.

Figure 1
Payload Specification and Design Process



2.3 Instrument Specification

The specification of the instrument is in terms of engineering parameters which can be directly related to the instrument design, verification and long-term performance. To illustrate the critical areas in specifying a particular payload, the specification process in a remote sensing instrument has been analysed.

- Radiometric specification, frequency, bandwidth, and polarisation of observation channels are chosen for the maximum sensitivity of the data to geophysical variables.
- Performance parameters are ideally specified to adequately ensure meeting the user products requirements, after processing and calibrating. The complexity and lack of complete analytical relationships describing the physical processes make the translation ill-defined.
- The sensitivity of parameters is also dependent on specific aspects of the system design.
- The retrievals of parameters are performed by combinations of channel measurement, the inter-channel variations are also therefore important in the performance.
- In practice the transformation into specification terms relies heavily on the performance obtained from previous instruments.
- In addition to the engineering parameters, implied limits on certain parameters at lower level, relating only to a particular sub-system may be defined (eg receiver linearity).
- Restrictions are imposed by mass, interface and physical size constraints to match the payload to a particular launch opportunity.
- The payload must be designed to guarantee a useful working lifetime. This necessitates high degrees of reliability and redundancy of essential system parts.

2.4 System Design

The system design is basically a trade-off procedure to ensure that the engineering parameters are met. Analytical and budgetary relationships are used to estimate performance in terms of individual engineering parameters for particular types of design. The system design process consists of matching available and achievable technology, such that the optimum design is arrived at to meet performance within the constraints. This is achieved by considering the most stringent requirements that define the most critical design features. It is then necessary to ensure the demands of other parameters can be met within that design. The trade-off comes where there is a conflict of parametric influence (for instance increasing antenna diameter gives better spatial resolution but poorer signal to noise performance).

The most difficult parts of this process are:-

- Parameters are treated independently, or at best on a case by case basis where interactions exist.
- Major design decisions may need subsequent reappraisal of enginering parameter performance and compliance to constraints.
- The impact on the geophysical parameter is not clear because of the complex relationship between the geophysical and engineering parameters. The real relevance of design trade-off in critical cases is therefore difficult to judge, and also in practice limited to a case by case consideration.

Figure 2
Payload Specification and Design Process (cont.)

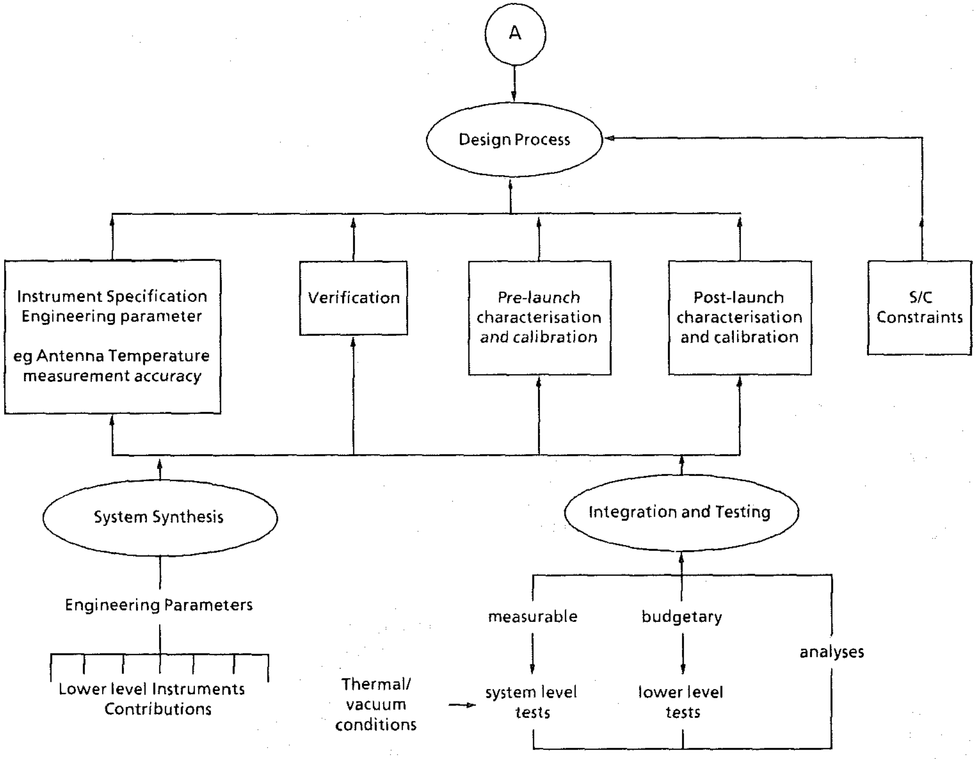
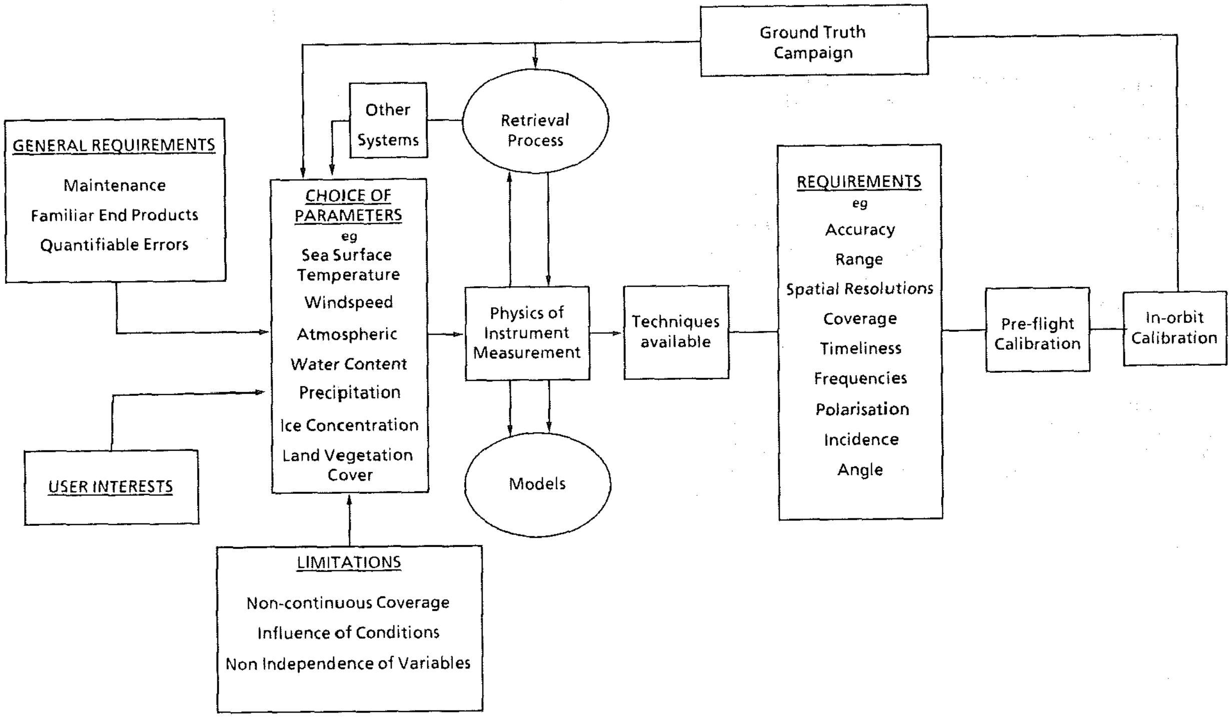


Figure 3
Factors in Specification Definition



3. Avionic Systems

3.1 Specification

An avionic system specification is in terms of the aircraft's ability to achieve its primary goal It can normally be defined in top level measureable parameters directly related to system outputs. For instance, this may be the physical error between the aircraft present position and the best system estimate based on a mix of sensor inputs. Individual sensor input sensitivities are derived during the specification and top level design stage and the system performance predicted. This is similar to the budgetary analysis and trade-off made for payloads, but it has to accommodate the more extensive functional options of an avionic system. The parameters however, are generally directly relatable to the system design, and can be measured and recorded.

The sensitivities are derived for particular designs by the use of models, to predict the expected system performance sensitivity based on individual sensor contributions. The magnitude and form of error sources are modelled in a number of realistic scenarios for each of the sensors in typical flight profiles, and the resulting overall system performance predicted. This modelling will include the loss of particular sensors and hence the performance of primary and reversionary modes can be analysed.

The form of the relationships linking many of the sensor outputs to the system parameters (eg ground speed to present position) are in the main well known even in the design specification stage, and hence analytically definable.

In more complex cases, where the system performance does include factors external to the aircraft, models are again used to assess the performance. In the case of military aircraft the final performance of an (unguided) weapon system, for instance is defined in terms of 'holes in the ground' the miss distance of a particular weapon in a particular attack mode. Here a number of uncertainties external to the aircraft are involved in the weapon trajectory, subsequent to the aimed release. Models of the physical process and system interactions are used to predict the influence of individual errors on the difference in actual and predicted on-board weapon strike position. The individual contributions to the miss distance are statistically combined for expected errors in various scenarios. The effect of each error contribution is obtained either analytically, relationships based for example on target geometery measurements, or they rely on perturbation of the modelled trajectory of the weapon by external effects such as the wind shear.

The possible scenarios and moding choice, if a number of sensors are available, make the number of combinations of the performance prediction cases very extensive. The final specification of cases has to be limited by user and designer agreement. Statistical analysis is used to extend the results to be fleet representative.

The use of modelling to assess the impact of external influences on the performance is the basis of the proposed technique of spacecraft payload specification optimisation currently being investigated for payloads (see section 6).

3.2 Design

The design of current avionic systems has had to respond to demands to vastly increase the complexity of functionality, moding and processing in individual equipment in the system. The corresponding distribution of functionality across equipments has led to the increase in distributed processing, as opposed to the earlier systems based on one main processor.

Systems consist of sophisticated equipment, each with their own software and functionality, distributed on one or more data highways. This calls for overall co-ordination, definition and control of system and software design and integration. The strategies adopted have led to the introduction of formal tools for requirement specification and the subsequent software system design and test documentation and implementation. Ref (1) details one such approach to demands of system design and integration.

The formal methodologies have precise rules for requirement specification and the subsequent corresponding specification of top level and detailed design. The tools allow automatic cross-checking for consistency and completeness during design review.

The complexitiy and cross functionality of distributed processing is not as yet so extensive in spacecraft systems. This is partly due to much of the demanding computation being performed off-line and not in real-time. Future missions to planetary targets will involve long signal delay times. In Earth observation systems advances in processor power, re-useable spacecraft, and the resulting more demanding requirements will call for greater system flexibility and response. Therefore the equivalent introduction of formal tools and methodology for specification and development of software are likely. Steps towards this are already underway with the rigorous control and review of individual processor software. The use and implemenation of formal design tools such as in avionic systems is an area that would benefit from consideration prior to the onset of specific demands. In the Hermes project, which straddles the two disciplines, formal design tools developed for avionic sytems are to be applied (Ref (1)).

4. Characterisation, Calibration and Verification

4.1 Satellite characterisation and calibration

On-ground characteristion is the process of taking measurements of the particular characteristics of the flight model eg measurement in ground ranges of the flight antenna pattern. Analysis is used in order to allow for measurement range uncertainty and to predict the additional influence of launch forces, in-orbit deployment, and zero-g and thermal/vacuum ambient conditions deformation.

Characterisation also includes the testing process of stimulating the integrated system over the ranges of orbital conditions (vacuum and thermal extremes) with known inputs representative of the scene or target to be observed. The outputs are then used to establish relationships between raw data output (voltage level) to inputs (brightness temperatures simulated by a dedicated target). Analysis is performed to compensate for the limitations of conditions and error sources in inputs.

Post-lauch characterisation consists of a specific pre-planned campaign, to make a one-off assessment of the particular characteristics of the system in-orbit. This is conducted after launch and prior to operational status. This will normally consist of the analysis of raw satellite data against defined targets or areas of known properties. In order to calibrate a radar, for instance, the pulse returns from corner reflectors on the ground are used to assess receiver gain and stability, determine the in-orbit antenna pattern, and determine the geo-location from the satellite attitude data. These are used to allow corrections to be incorporated into the ground processing.

Specific ground campaigns are carried out, typically in the first six months of operation, to measure the geophysical conditions existing concurrent to system overpass . This is particularly important in many remote sensing instruments which often have a diverse set of products with ill-defined relationships between them. The comparisons are used to optimise the retrieval algorithms. The ability to measure over a sufficiently large area on the ground in a short time and the accuracy of the geophysical parameters measurement itself is also a limiting factor in achieving the overall system performance.

Some activities are continued over the entire operational lifetime of the satellite, in order to assess the status of the system as it ages. This may include observing specific regions of known characteristic (eg desert, rainforest, ocean) and comparing them regularly to evaluate the receiver gain and stability to use for telemetric setting of the gain loops. This is to produce consistent data throughout the satellite lifetime for long-term user studies.

The performance of the sytem as it fluctuates with time and ambient conditions can also be corrected using an on-board calibration system. This requires measurement of known references such as a temperature controlled source or cold space at certain points in the instrument scan. The sources and the influence of error contributions for the particular calibration design are important factors in assessing performance.

4.2 Satellite verification

Verification of payloads also takes place both on-ground and in-flight. Verification is the demonstration that the system is fulfilling the requirements of the engineering specification. This does not guarantee, however, that the user requirements are being met. Ideally on-ground verification takes place both as confirmation of launch readiness, and from the contractor point of view, to demonstrate compliance in a controlled environment. This is to cover unexpected degradation of the performance by external factors eg incorrect deployment, outside the specification. It is also necessary when a single flight model is built and lost in a launch failure. In this case any performance related payments have to be resolved solely from on-ground verification. It takes the form of formal running of the system ground tests and agreement of the complementary analysis. The definition of completeness of the tests and the necessary associated analysis therefore forms an intrinsic part of the specification and design procedure. The criteria for acceptance is also a critical area to resolve and agree.

The parameters measured during verification require a suitable assessment method. These are usually related to the engineering parameters. The complexities and uncertainties between the geophysical/engineering parameters make the definition and agreement of tests and analysis a critical area in the specification process. Definition is normally resolved on a case by case basis.

In-flight verification is either based on, or in parallel with, the characterisation activites. The system performance is compared with ground measurements of the same parameter or well-defined conditions that have been introduced for verification.

The difficulties and critical areas of the design process suggests the need to have an overall assessment model taking into account all aspects of the chosen system design interactions available. This model should preferably relate to final end user products. Such a model is being established and used to investigate the opimisation of payload specification and is described in Section 6.

4.3 Comparison with Avionic Systems

The comparison with satellite characterisation techniques in avionics includes such processes as ground harmonisation, or the measurement of HUD (Head-up Display) or radar boresight to aircraft LFD (Longitudinal Fuselage Datum). This uses measurement references to physically align the display or sensor to the reference within the system and measurement tolerance. It has been used (at least experimentally) to measure specific errors on a particular aircraft eg radome distortion in order to define real time correction processes in the system. This is similar to payload characterisation. Aircraft compensations however, must be on-board rather than post ground processed and respond in real-time. The greater and distributed processing in avionic systems being developed make this technique a viable future option to minimise individual errors. It would be advantageous in reducing the requirements on mechanical harmonisation, at the expense of specific measurement on each aircraft.

Characterisation and calibration is far more important in satellite payloads than in avionics for a number of reasons.

- The greater, but predictable, extremes of ambient conditions
- The lack of flexibility to alter the system subsequent to launch. This in turn is partly caused by the constraints on reliability and weight.
- The inability to repeat the ground measurement.

The operational acceptance criteria of aircraft is relatively straightforward in comparison to spacecraft payload verification. The performance parameters can be measured directly in a number of dedicated flight trials. Subsequent system optimisation or repeated or extended trials can be performed in cases of uncertainty.

5. Integration and Testing

5.1 Satellite Payloads

The assembly integration and testing of the payload depends to a great extent on 'how much' of a system it is. Early spacecraft systems had relatively simple single observations to perform although in a hostile but definable environment. With an increasing complexity of functions and a number of co-temperaneous observations, the testing and result evaluation demand becomes exponentially greater.

The design implementation, integration and testing activities rely on the comprehensive testing of individual items and equipment followed restricted full system testing.

The reliance on lower level testing , the transition to full system level testing, and the imposed restrictions on system level testing contrast markedly with avionics. The extensive integration phase, building up the full system from chains of equipments fulfilling particular functions or modes, is virtually absent. The causes of this present philosophy are due to the currently unique features summarised below.

- A very limited number of satellite payloads are built (one engineering and a number of flight models), with weight, reliability, interfaces, and the need to meet specific launch opportunities of the utmost importance. On-ground running of the flight model payload time comprises part of its working life and is therefore restricted. It is also restricted in the amount of switching between modes and redundancies that can be made. Weight, reliability and performance constraints all mediate against specific test monitoring points being built into the spacecraft.
- Specific test equipment to simulate over the full range of inputs to the instrument are expensive and difficult to make representative of the satellite operational conditions. A radar echo pulse from a target at orbital distances (500 km low Earth remote sensing to 36000 km Geosynchronous) would require literally miles of delay line.
- Simulation of the environment for the whole system configuration are only possible in very restricted test facilities, with time and program restrictions as well as as cost. The environments that need to be simulated include thermal, vacuum and solar radiation simulation.

As hardware development procedes and individual test results become available for particular items, the analytical budgetary estimates are updated to monitor the expected system performance. Shortfalls in the performance have to be either corrected or traded-off by reductions in other parts of the performance budget. This is particularly difficult to evaluate in areas where interactions and inter-dependancies exist.

The system tests made are pre-defined and run in a set sequence under automatic control of the EGSE (electrical ground support equipment). Tests consist of a range of representative variations of the inputs to the instrument, over a limited range of modes, settings, and redundancy configurations etc. The EGSE and test sequence is designed to allow very rapid complete system tests, and automated result production often including a Pass/Fail criteria assessment. It is also designed to enable repeat testing after spacecraft shipping to other testing facilities and a launch site where a limited subset may be run.

The 'system level' tests are primarily made at ambient conditions. Subsequently, restricted subsets may be made under thermal/vacuum conditions though possibly not in full orbital configuration (ie without antennae using dummy loads) due to facility space restrictions.

Any shortfalls revealed in engineering or flight model testing demands remedial action, or trade-off by enhancing other item performance or design. This is very costly and perhaps not feasible in the launch window timescales. Performance waivers may have to be sought and agreed with the customer. However, the true assessment of the impact of the shortfall in geophysical terms remains subject to the uncertainties present at the specification stage.

The analysis of both lower level results, and system level tests, would be optimised by being able to assess true system sensitivity in user terms.

To date the philosophical implemetation has proved demanding, but adequate, as payloads have been comparatively inflexible systems able to meet a rather limited number of functions or sets of observations. The ability to optimise the performance based on operational results and changing requirements may demand that satellites become more flexible and have correspondingly greater functionality. The functionality must be in-built and therefore tested. The future sytems therefore are likely to need increased complexity of design, more on-board processing or the introduction of independant bus systems, in much the same way that is currently used in avionics. The build up of the instrument from lower level may result in problems only being apparent at system level. This is frequently experienced in avionics, and requires that flexibility and facilities for system testing need to be correspondingly enhanced.

The critical area is the localisation and diagnosis of system errors, which is also very time consuming. It is achieved in avionics by provision of flexible simulation and monitoring tools and points throughout the system . Performance, weight and reliability restricitions of payloads are the mediating factor against the provision of specific test ports. The provision of flexible simulation tools would appear to be another area that should be considered if greater payload system flexibility and functionality is to be achieved. Future system design and integration strategies will have to reflect this.

5.2 Avionic System Comparison

The avionic system behaviour is tested out over a far more diverse set of simulated conditions, and functional mode combinations. This reflects the more extensive control options involved in piloted aircraft for the extensive ranges of possible aircraft roles and scenarios.

Integration consists of a phased build-up of the individual equipments to establish the cross-equipment functionality. This is realised by the use of dedicated integration rigs with associated equipment benches.

Each equipment has individual test facilites, STTE (Special-to-Type Test Equipment), providing interface and stimulation for sensors. Integration rigs allow functionally dependent groups to be linked and the full configuration to be built-up in phased stages. The remaining parts of the system are simulated by specifically designed tools (normally general purpose for use on a number of projects). These tools (data bus and other interface simulators and data simulation programs) also provide monitoring facilites.

The time and requirements on integration are becoming increasingly critical, especially with the advent of multiple bus systems where hardware, software, firmware and even differences in standard protocol interpretations can be very difficult to localise at the system level.

Much time is required in the investigation of anomalies caused by complex and unexpected interactions of the system. This requires the specific generation of individual equipments stimulation to be co-ordinated and the ability to monitor a variety of signals at different points in the system.

The development of integration package tools and facilities to deal with different types of aircraft is being developed as part of the formal methodology. This radically increases the cross-checking and testing of individual software items prior to integration of equipment software, It has therefore also reduced the numbers of pure programming errors that are found at rig integration stage. However, true system problems involving an interaction between processors, or an error, or particular exception case in the design requirement are not revealed until the rig integration stage and are extremely difficult to identify and localise.

It is noticeable that the new strategies and critical area of avionic software development parallels the payload integration methodology. There is reliance on comprehensive low level testing, and subsequent system level testing.

This has to be defined and assessed by the overall system designer and co-ordinator, with the aim to establish functions and interface response over a wide range of conditions before system integration. The aim being to reduce integration time and full system configuration testing. It does however require specific test equipment over and above the normal STTE requirements, and not appropriate for flight-line maintenance.

The culmination of the integration phase build-up leads to ground testing of the full system. This uses formal repeatable test procedures to establish interface functions and the performance in operational scenarios. The tests are structured as specific missions from pre-take off to landing. These formal procedures are the basis of flight release, and are repeated for successive update of software and hardware standards.

The running of these clearance tests is an area where avionics may benefit from the experience and techniques of payload methodolgy.

The automatic running, assessment and reporting of the pre-defined test procedures is highly desireable for consistency, quality assurance and particularly timescale reasons. Clearance of modified on-board software standards would especially benefit from such automation. The use and definition of requirements and techniques for satellite payload EGSE could therefore provide a fruitful known working baseline for future tools and procedures development.

6 Optimisation of Satellite Payload Specification Methodology

In order to predict the performance of a satellite payload in a manner broadly similar to that used in avionics a model has been developed. This uses a mathematical model of the payload and scene to link the instrument measurement and geophysical conditions for particular designs and performance of individual items of the payload.

A system synthesis is initially made for the type of system to be optimised. This synthesis comprises a breakdown showing the interactions and contributions to the system measurement performance. An example of part of such a synthesis is shown in Figure 4 for a passive microwave radiometer. It illustrates the interactions of the spatial and geometric design loop.

Using corresponding analytical relationships a mathematical model of the system synthesis has been established. Fig 5 is a top level flow chart of the program. The model runs interactively such that the user can assess the performance and examine the implications of each design decision and trade-off. This has been used to investigate the senstivity of the system performance to changes in design parameters or imposed constraints. By systematically incrementing specific input parameters, their influence on overall performance can be analysed for any particular design. The model assesses the performance in terms of engineering parameters for a specified worst case assessment scene variation, expressed as a contrast in brightness temperature (the temperature of a black body that would radiate the energy observed). Fig 6 illustrates some results from the initial model. This shows the spatial resolution achieved by a particular design as the spacecraft altitude and the antenna scan rate vary. The resolution depends upon the observation channel frequency and for this instrument 6 channels at frequencies between 6 and 90 GHz, particularly sensitive to various geophysical conditions, have been chosen. The scan rate is calculated such that the individual beam footprints on the ground overlap by at least 30%, which is typical of the user requirements for the geophysical parameters being measured. In the model derived it is possible to vary a large number of instrument parameters and observe the effect on instrument performance.

It is intended to extend the model to representative scenes for particular geophysical conditions and derive the instrument influence of the scene measurement in brightness temperature terms, and subsequently the sensitivity of the geophysical parameters, to changes in the instrument design.

7. Conclusions

This paper has compared the methodolgy and techniques used in the specification, design and verification of spacecraft and aircraft systems. The reasons for the differences and the particularly critical areas have been identified.

Consideration of current trends and future changing demands has been made. The areas where one discipline might fruitfully apply the experience or techniques of the other have been discussed, and a summary is included in Table 1.

An example of a model being developed to optimise satellite payload definition has been described.

8. Acknowledgements

The model described in this paper and the research into satellite payload specifiction has been carried out with support of a SERC CASE Studentship with British Aerospace Space Systems.

9. References

1. Schirle P, Avionic Systems Functional Analysis and Specification, ICAS 90-2.5.1.

Table 1
Summary of Possible Areas of Cross Discipline Application

	Critical Area	Technique	Para
SPACECRAFT FROM AIRCRAFT	Geophysical/Engineering parameters and user/designer requirements specification	System synthesis and sensitivity modelling	3.1, 6
	Increasing functionality and flexibility in design	Distributed processing with associated formal specification methodologies and tools	3.2
	System integrated testing	System test rigs with flexible monitoring and simulation facilites	5.1, 5.2
AIRCRAFT FROM SPACECRAFT	Characterisation and compensation of particular errors	On-board processing	4.3
	Automatic running of clearance tests	Definition of testing and tools during design	5.1, 5.2

Figure 4
Example of Part of System Synthesis

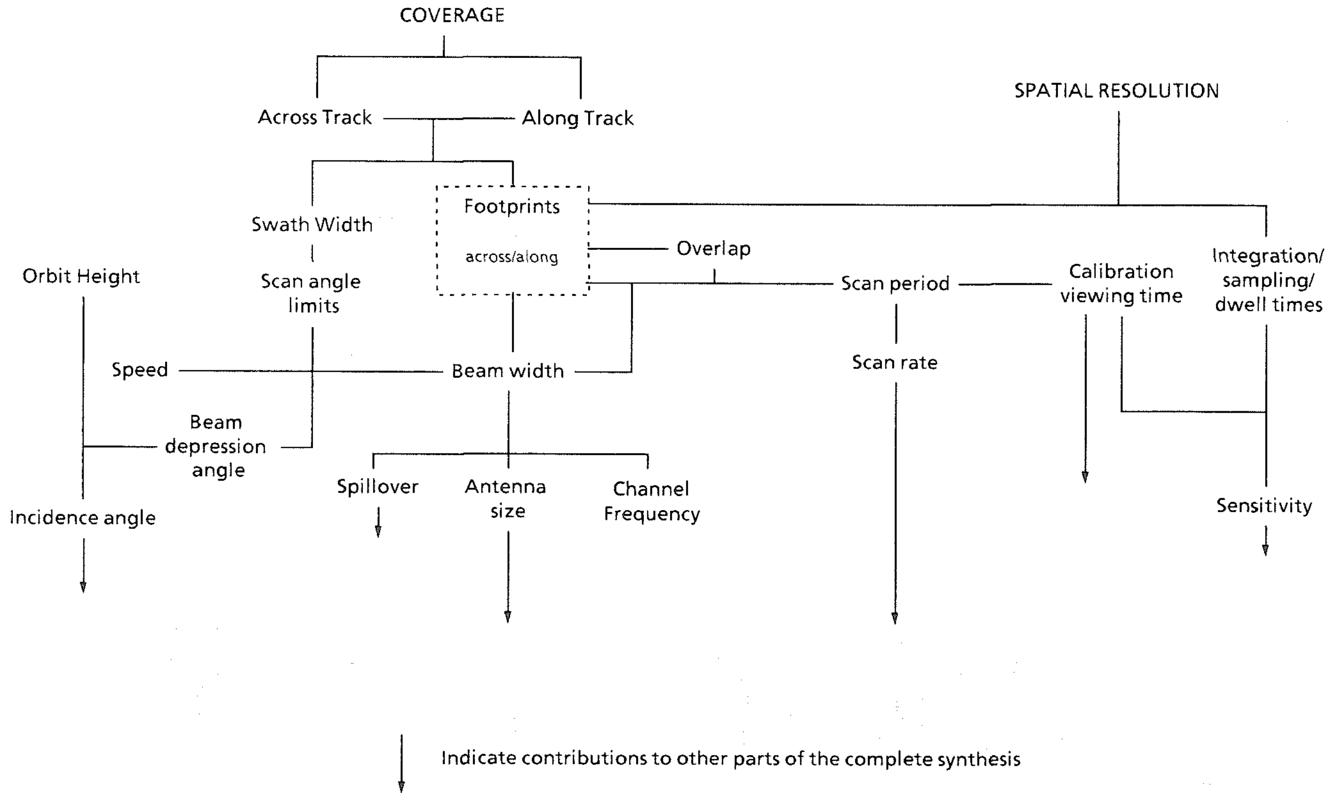


Figure 5
Flow Chart of Model

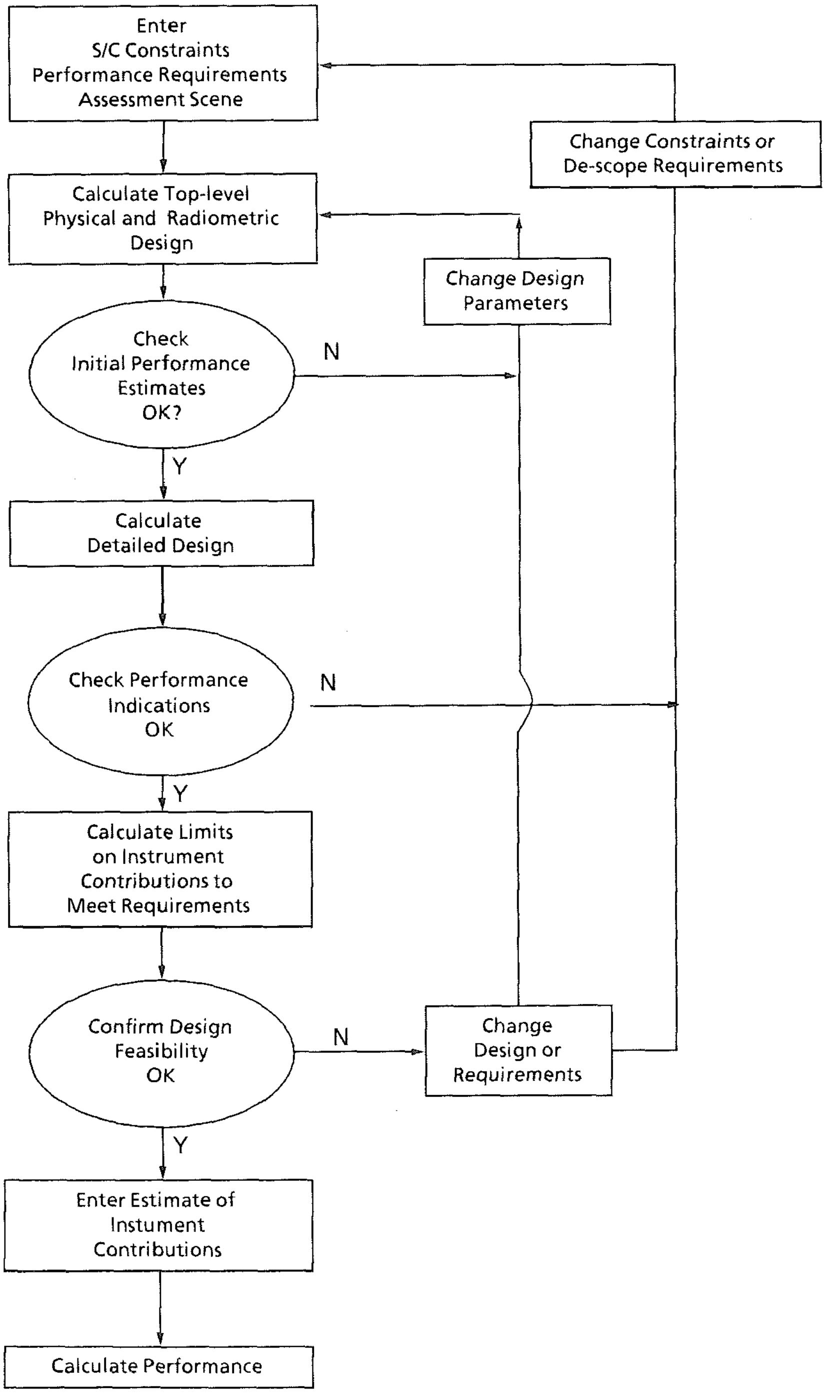


Figure 6
Model Results for Resolution Sensitivity of 6 Channel Scanning MW Radiometer.