Evaluation of a space qualified long life flight computer server

Vicente-Vivas E.[1], Mendieta J.F.J.[2], Calvillo T.A.[3], Tapia R.M.[4]

[1] Instituto de Ingeniería, UNAM, DF, México, evv@servidor.unam.mx
[2] CICESE, Ensenada BC., México, jmendiet@cicese.mx
[3] CITEDI, IPN, Tijuana BC., México, calvillo@citedi.mx
[4] CIMAT, Gto., Gto., México, max@fractal.cimat.mx

Abstract. The first ever fully designed Mexican microsatellite is to be assembled and tested by several federal research institutions from the country. Some satellite subsystems are already done, few other are about to get finished and a couple of them are still under development stage. One of the already available subsystems is the space qualified computer server (SQCS) along with its operations software for both the space and ground segments, as well as associated tools that enabled the full subsystem validation regardless the physical presence of other complementary satellite subsystems. The single points of failure from the SQCS architecture were developed with cold standby redundant modules to improve hardware reliability. In addition reconfiguration capabilities commanded by digital signals were also considered, thereby allowing the extension of satellite life in the presence of important SQCS failures. Under this scenario, this paper outlines the hardware and software tools specially created for SQCS validation purposes, as well as results of a reliability study to predict the server behaviour based on the exponential failure law, the military standard MIL-HDBK217f notice 2 and MatLab software.
Key words: computer architecture, flight computer, hardware reliability, computer evaluation, Markov models, microsatellite.

Resumen. El primer microsatélite completamente diseñado en México está por ensamblarse y certificarse con la participación de diversos centros de investigación nacionales. Algunos de sus subsistemas ya se encuentran concluidos, otros están a punto de terminarse y solo un par de ellos se encuentran aun bajo desarrollo. Uno de los subsistemas terminado es el servidor de cómputo de calificación espacial (SCCE) junto con su software operativo tanto del segmento espacial como del segmento terrestre, así como sus herramientas que permitieron validar operaciones del subsistema sin necesidad de contar con la presencia física de los subsistemas satelitales con los que interactúa. Los puntos más vulnerables del SCCE fueron diseñados con partes de refacción para mejorar su confiabilidad operativa. Adicionalmente se le agregaron capacidades de reconfiguración por medio de señales digitales, para permitir de esta forma extender la vida útil del satélite ante fallas del SCCE. Ante este panorama este trabajo describe las herramientas desarrolladas en hardware y software para propósitos de validación del

SCCE, así como los resultados de un estudio de confiabilidad que predicen el comportamiento del servidor de cómputo con base en la ley exponencial de fallas, la norma militar MIL-HDBK217f y software escrito en Matlab.
Palabras clave: arquitectura de cómputo, computadora de vuelo, confiabilidad de hardware, evaluación de computadora, modelos de Markov, microsatélite.

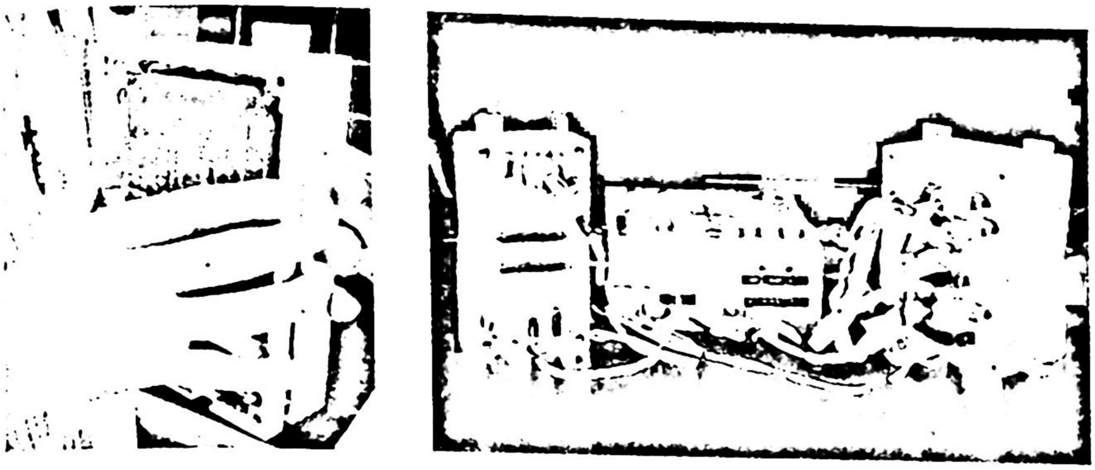
1 Introduction

Satex microsatellite project is a multiinstitutional Mexican effort to develop domestic technology in the space field. The microsatellite, [1], will weight about 55 Kgs, with cubic shape, solar panels on four of its faces, five experiments, and 5 microcomputers interconnected through a redundant LAN. The payloads will consist of an optical communications downlink, a Ka band communications uplink, a minimal survival system to control satellite elementary operations, a digital camera for remote sensing studies and a computer architecture experiment planned to apply automatic maintenance to the SQCS, the most critical microsatellite computer, [2].

The microsatellite project constitutes an excellent opportunity for hands on training of human resources from all over the country in order to generate a strategic infrastructure considering the feasibility to develop more sophisticated satellites in the medium term. Moreover, assuming continuous activities in the area and considering some kind of successes in the medium term, possibilities of commercial implications exists for products and technology developed under the project. Therefore the space subsystems fabricated for Satex were designed and built according with the strong limitations of space vehicles in terms of weight, volume, and electrical power. In addition, hardware reliability enhancement through the use of redundancies in critical parts of the instrumentation was envisioned. In particular, the SQCS was designed and constructed with reconfiguration capabilities and cold standby spares to withstand important hardware failures. Besides considering that the use of commercial-off-the-shelf (COTS) components is becoming an important practice to launch state-of-the-art electronics into LEO orbits, the Satex mission also considered the viability to experiment the utilization of COTS parts protected for space flight.

From the beginning of the project steps were traced to develop a reusable fault-tolerant flight computer server and use it as the automation backbone for the space vehicle, [3]. A complimentary goal was to build up a reusable SQCS to reduce the development and production costs for future space projects.

In this way the SQCS was developed with: a reconfigurable architecture that contains up to three single board microcomputers (SBC); one digital switching unit that enables any one of the SBC to be connected to the satellite instrumentation; multiplexing unit to capture 48 electrical signal from satellite sensors; hardware for redundant LAN that combined with dedicated software admits fault-tolerant communications among satellite computers, [4]; latch-up protection for COTS parts as well as I/O connectors. By financial reasons the Satex's SQCS was integrated with just two SBC into a space qualified aluminium cabinet which integrates five printed circuit boards, each one with electronic components on both of its faces and mostly of them of surface mount type, figure 1.a. Information regarding SQCS design and protections for use in space environment can be found in [5].



(a) (b)

Figure 1. Space qualified Computer Server: (a) Stackable printed circuit boards; (b) Flight model under testing with CESSM module at the left, satellite simulator at the centre and SQCS at the right.

2 Hardware and software tools developed for SQCS validation

To allow the validation of SQCS hardware as well as its progressive software development must of the onboard satellite equipments were needed in continuous working stages. However the different satellite subsystems were all together grown in parallel fashion and therefore were unable for combined testing purposes. By this reason, since the starting of the project provisions were made to develop hardware and software tools for SQCS validation purposes. The following hardware and software tools were developed throughout the last years: a satellite simulator (SIMSAT), an emulation software for satellite payloads called SOFDEVO and the earth station software (ESS). These tools allowed the progressive development of both SQCS hardware and software.

3 Satellite simulator

The satellite simulator shown in figure 1.b was constructed to allow the SQCS to interact with satellite peripherals such as sensors, actuators, payloads and other subsystems. The SIMSAT contains: 48 passive sensors to provide real telemetry collection; electronic representation for UHF radios and magnetic coils; gravity gradient release emulation and 10 I/O connectors of different size for interconnection with SQCS. Furthermore contains several analog switches to manually control the SQCS reconfiguration as well as push buttons to command the execution of programs either from PROM or from SRAM memory. In addition SIMSAT allocates LAN ports to attach up to 4 personal computers, each one running the software SOFDEVO, for payload emulation purposes and consequently for SQCS operations validation.

4 SOFDEVO software

SOFDEVO allows the depuration, emulation and operative validation of software for all or any one of the satellite computers, figure 2.a. In consequence, the software allowed the depuration and operative validation of SQCS hardware and software. For this purpose SOFDEVO was planned to grow in parallel with all other satellite subsystems. Its operation is based on the fact that all computers on board the space vehicle are connected through a redundant LAN where communications traffic generated by computing nodes is found. In this way SOFDEVO runs dedicated software for every emulated payload, establishing therefore the payload operating behaviour. The software manages network protocols, fault-tolerant network attributes [4], and also contains all kind of programmed answers for network queries related the payload. However, some software features are allowed to be programmed advance by the user through the help of menus to generate automated answers according with specific needs. Whenever the last process is required it has to be programmed before starting an emulation process in such a way that SOFDEVO real time performance is achieved.

Moreover SOFDEVO contains two data windows, one shows decoded messages collected from the network, allowing the user to be informed about real time satellite network operations. The second window shows the answers generated by SOFDEVO when network enquires are directed to anyone of the emulated payloads.

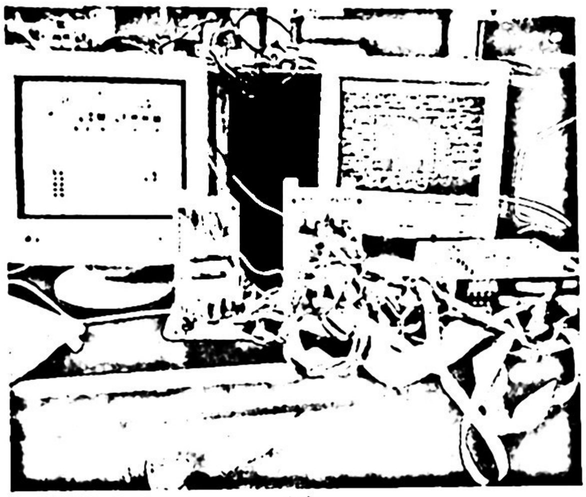
On the other hand SOFDEVO allows the programming of fault insertion processes which are emulated in combination with LAN protocols whenever payload diagnostic results are generated in order to validate satellite software under the presence failures. By these reasons the software was invaluable for SQCS hardware validation as well as for SQCS software developing process.

5 Earth station software

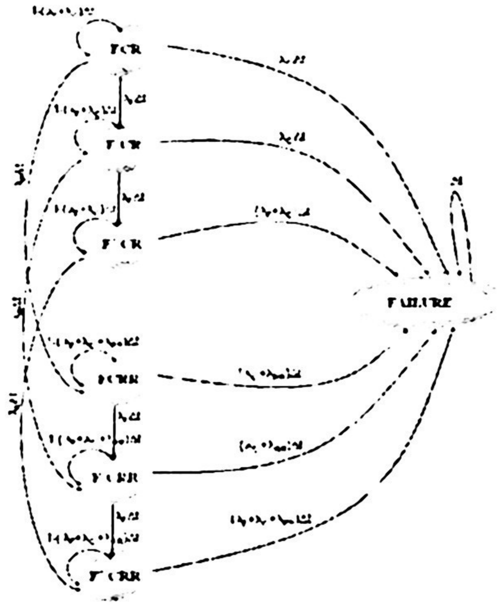
The earth station software (ESS) was also created in parallel fashion along with other satellite subsystems according with needs and characteristics from the satellite flight software. This approach allowed the design and the implementation of data frames, commands and communications protocols among satellite and ESS. From the beginning of the project the initial progresses in satellite automation software enabled the validation of operations among satellite instrumentation and ESS. In this way the continuous verification of automatic processes took to the progressive development of the whole SQCS hardware and software.

Moreover the project offered enough available time to generate three updated versions of ESS from which the last one contains a highly visual environment where satellite telemetry is exhibited with digital animations and virtual instruments, figure 2.a. In addition the ESS contains a set of menus from which following actions can be controlled:

- Communication speed among satellite and earth station.
- Automatic satellite search.
- Programming of alarm thresholds for anyone of the satellite sensors.
- Transmission of new programs to the SQCS.
- Definition of a satellite telemetry mission (Normal or Special type).
- Telemetry downloading.
- Statistics of initialization procedures performed by the SQCS.
- Telemetry displaying with virtual instruments for up to 64 satellite sensors, 48 of them obtained by the SQCS.
- Animated displaying of satellite equipment status.
- Numerical telemetry displaying.
- Image acquisition programming.
- Image downloading and fast local view.



(a)



(b)

Figure 2. (a) SQCS validation in laboratory; SOFDEVO software at the left and ESS software at the right. (b) Markov model describing SQCS operating states.

6 SQCS validation

The SQCS hardware was progressively validated in several development stages. At the commencement of the project must of the electronic designs were validated in laboratory with the help of breadboards and COTS components. While waiting the arrival of military qualified components some PCBs were designed and sent for production. Later the PCBs were carefully checked and then parts assembling took place with the application of continuous testing to guarantee PCB operation. The overall process conducted to the identification and elimination of errors as well as to the development of PCB updated versions for every one of the five electronic cards that comprise the SQCS architecture. At the same time preliminary software testing procedures were achieved through the direct connection of a single SBC either to SOFDEVO or to ESS. Later on testing was carried out among ESS, SBC and SOFDEVO. The progressive development of referred subsystems took to the validation approach seen in figure 1.b and figure 2.a. Where satellite sensors emulation was replaced with the module called "conditioning electronics for satellite sensors and maintenance" (CESSM). By these means the SQCS was continuously validated with the CESSM flight model and updated versions of ESS and SOFDEVO. Successfully testing involved following actions:

- Transmission of new programs from ESS to the SQCS.
- Programming and transmission of satellite missions at ESS.
- Execution of either new programs or new missions at SQCS with SIMSA and SOFDEVO support.
- Telemetry transmission from SQCS to the ESS.
- Telemetry downloading and consequently telemetry displaying at ESS.

7 Reliability study of SQCS hardware

In order to know the reliability gains introduced by the use of cold standby SBC's and redundant LAN under space environment an analysis based on the exponential failure law, the military standard MIL-HBK217f notice 2 and Markov models was elaborated.

To obtain the failure rates for each one of the electronic components contained in SQCS the exponential failure law was employed as well as the calculation procedures for failure rates suggested by the military norm "MIL-HDBK-217f Notice 2", see table 1.a. Full information about the procedures to calculate reliability rates for any kind of electronic component was directly obtained from the Department of Defence of the USA.

(a)

Description	Acronym	Failure rate
16 bit RISCM	SAB80	8.36297E-07
16 bit EDAC	EDAC	9.12533E-08
SRAM memory (128K x 8)	RAM128	1.01393E-07
SRAM memory (512K x 8)	RAM512	3.11022E-07
EPROM memory (32K por 8)	PROM	1.30852E-08
Comparator LM139FK	COMP	3.08985E-08
Nand gate SN54HC00FK	NAND	1.0771E-08
Or gate SN54HC32FK	OR	1.0771E-08
And gate SN54HC08FK	AND	1.0771E-08
Operational amplifier TLC2201FK	AMP2201	3.54674E-08
Operational amplifier TLC271FK	AMP271	3.64674E-08
Digital multiplexer SN54HC157FK	MUXDIG	1.1571E-08
Line driver SN55189FK	LD189	3.86674E-08
Line driver SN55188FK	LD188	3.86674E-08
Analog multiplexer CD4053BM	MUX4053	2.52931E-08
Monostable MM54HC221A	MONO	3.78951E-08
40MHz oscilator	XTAL	0.000000015
Hexfet (MOSFET) IRFF130	IRFF	1.16E-08

(b)

Mission	Sucess Reliability
1 year	0.99
3 years	0.97
5 years	0.95
10 years	0.9

Table 1. (a) Calculated failure rates for SQCSs' electronic components. (b) Reliability values given by Hoffman for electronic space equipment

Once the failure rates were obtained, the SQCS was divided into modules: SBCs, switching unit, and so on. Afterwards each module was analyzed to check for serial or parallel arrangements. In this case, every module was represented with a failure rate whose value depends on the determination of the failure rates for every one of the grouped electronic components. Particularly, the failure rate was obtained by applying combinatorial techniques and the exponential failure law [6]. Then, in association with components shown in table 1.a the following failure rates for SQCS modules were obtained:

lamda_2_MONO_en_P = -log(1-(1-exp(-(1/2)*MONO))^2) .

lamda_2_HEXFET_en_P = -log(1-(1-exp(-IRFF))^2) .

lamda_2_MUX4053_en_P =-log(1-(1-exp(-1/3)*MUX4053))^2) .

R = LD189 + AND +(3/4)*AND + LD188 + (1/4)*OR + (1/4)*AND .

RR = LD189 + AND + (1/2)*NAND + (1/4)*AND + LD188 + (1/4)*OR .

C = (1/4)*MUXDIG + (2/3)*LD188 + (3/4)*MUXDIG + (2/3)*MUX4053 + MUXDIG + (2/3)*MUX4053 + (1/3)*MUX4053 + 2*lamda_2_MUX4053_en_P + (2/3)*MUX4053 + (1/4)*OR + (1/2)*LD188 + 2*lamda_2_HEXFET_en_P + 2*lamda_2_HEXFET_en_P + (1/4)*OR + (1/4)*AND + AND + (1/2)*OR + MUX4053 .

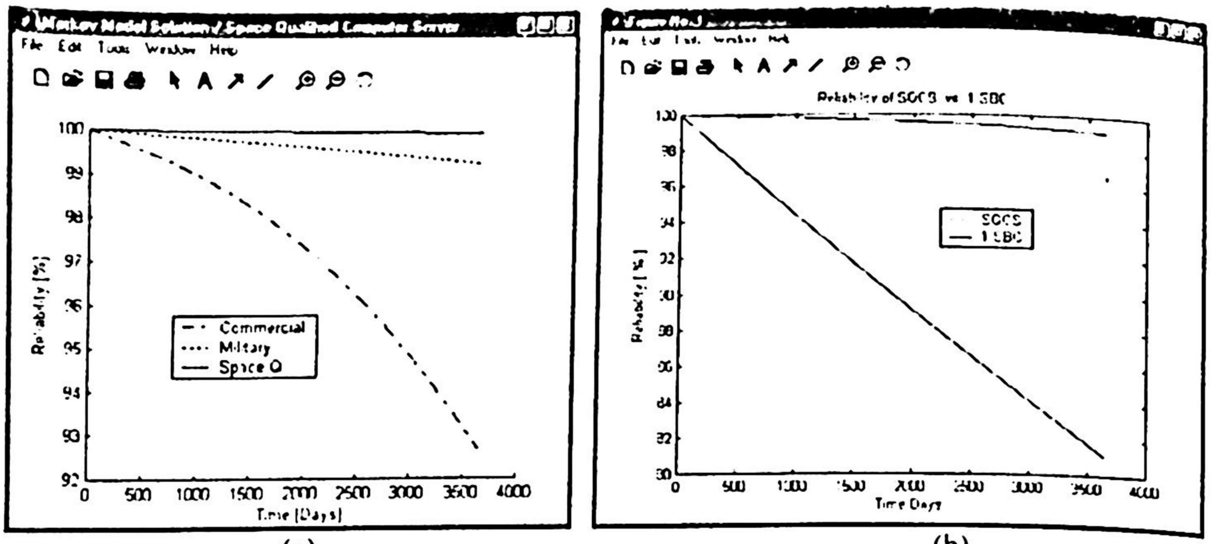
F = XTAL + SAB80 + 2*PROM + 2*RAM128 + 2*RAM512 + RAM512 + RAM128 + EDAC + (1/2)*AND + (3/4)*OR + (1/2)*NAND + (1/2)*OR + NAND + (3/4)*OR + (3/4)*AND + AMP2201 + AMP2201 + AMP271 + (1/4)*LM139 + LM136 + (1/4)*OR + (1/4)*OR + lamda_2_MONO_en_P + (1/4)*OR + (1/4)*OR + (1/4)*LD188 + 2*lamda_2_HEXFET_en_P .

From these modules the participation of spares was analysed to generate the Markov model for SQCS architecture, where λ_F stands for SBC failure rate, λc is the failure rate for the switching unit, λ_R is the failure rate for main LAN, and λ_{RR} is the failure rate for redundant LAN, figure 2.b. In this figure the state titled as FCR denotes that SQCS operates with main SBC symbolised with letter F (from three alternatives, F, F′ and F′′), the switching unit designated with letter C, and main LAN indicated with letter R (from two alternatives, R and RR). Once generated the Markov probabilistic model, the following Markov equations were generated.

$$p_{FCR}(t+\Delta t) = p_{FCR}(t)(1-(\lambda_F+\lambda_C)\Delta t)$$
$$p_{F'CR}(t+\Delta t) = p_{F'CR}(t)(1-(\lambda_F+\lambda_C)\Delta t) + p_{FCR}(t)(\lambda_F \Delta t)$$
$$p_{F''CR}(t+\Delta t) = p_{F''CR}(t)(1-(\lambda_F+\lambda_C)\Delta t) + p_{F'CR}(t)(\lambda_F \Delta t)$$
$$p_{FCRR}(t+\Delta t) = p_{FCRR}(t)(1-(\lambda_F+\lambda_C+\lambda_{RR})\Delta t) + p_{FCR}(t)(\lambda_R \Delta t)$$
$$p_{F'CRR}(t+\Delta t) = p_{F'CRR}(t)(1-(\lambda_F+\lambda_C+\lambda_{RR})\Delta t) + p_{FCRR}(t)(\lambda_F \Delta t) + p_{F'CR}(t)(\lambda_R \Delta t)$$
$$p_{F''CRR}(t+\Delta t) = p_{F''CRR}(t)(1-(\lambda_F+\lambda_C+\lambda_{RR})\Delta t) + p_{F'CRR}(t)(\lambda_F \Delta t) + p_{F''CR}(t)(\lambda_R \Delta t)$$
$$p_{FAILA}(t+\Delta t) = p_{FAILA}(t)(\Delta t) + p_{FCR}(t)(\lambda_C \Delta t) + p_{F'CR}(t)(\lambda_C \Delta t) + p_{F''CR}(t)((\lambda_F+\lambda_C)\Delta t)$$
$$+ p_{FCRR}(t)((\lambda_C+\lambda_{RR})\Delta t) + p_{F'CRR}(t)((\lambda_C+\lambda_{RR})\Delta t) + p_{F''CRR}(t)((\lambda_F+\lambda_C+\lambda_{RR})\Delta t)$$

The obtained equations can be represented by P(t+Δt) = [A] P(t). Afterwards, the vector of probabilities to stay at each one of the model states was extracted, in such a way that grouping the SQCS success states the survival reliability was determined. To make the calculation of such a vectors an interactive software in Matlab was generated to plot reliability curves for variable times.

To highlight the overall benefits of SQCS hardware (assembled with 3 SBCs) a reliability comparison among three different implementations was performed, one assembled with COTS electronic components, another assembled with military components and a last one assembled with space qualified electronic parts. Figure 3.a shows the reliability results for three different SQCS server versions. The highest reliability is obtained when the computer is assembled with space qualified electronic components and the lowest one is achieved with COTS parts. However the space components are expensive and require longer arrival times. Consequently the best reliability-cost relation is obtained with military components.



(a) (b)

Figure 3. Reliability results for SQCS (assembled with 3 SBC) in a 10 year time period: (a) For three SQCS versions; (b) SQCS and a single SBC both of them with military parts.

The reliability analysis shows the advantages of using military qualified electronic parts as well as the improvement obtained from using spares to increase the expected operational life for the SQCS and therefore for the satellite.

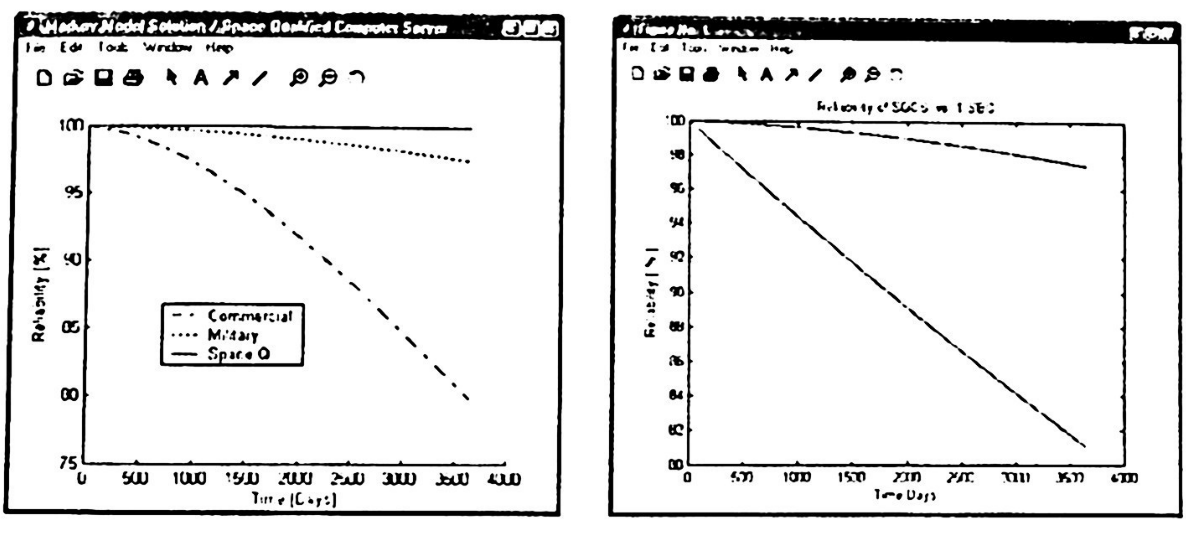
In figure 3.a the reliability obtained for SQCS assembled with 3 SBC in a one year time operation is important because represents the minimal expected life for the satellite. A reliability of 99.94 was obtained for this time, showing a very good forecast because of the spares included for the single points of failure from the architecture. In the paper from Hoffman [7] some reliability values that space equipments have to accomplish are given, see table 1.b. As seen, the SQCS assembled with military parts fulfills the Hoffman's reliability requirements.

In figure 3.b the reliability curves for a SQCS (assembled with 3 SBC) and a single SBC are shown. From this figure the reliabilities for a single SBC are as follows: 97.9, 93.8, 89.9 and 81.2 for 1, 3, 5 and 10 years of operation, respectively. By comparing last reliability values with reliability data given by Hoffman [7] we may conclude that a non redundant SBC assembled with military qualified parts does not accomplishes the reliability indexes required by electronic space equipment. This is the quantitative justification to develop a SQCS with cold standby spares in order to increase satellite survival possibilities.

As also shown in figure 3.b an expected reliability of 0.95 for a single SBC is reached in 2.44 years time period. On the other hand, a reliability of 0.95 is important in aeronautical applications [8], because once an electronic equipment reaches this value preventive maintenance has to be programmed on it in order to avoid unexpected failures. Besides, electronic equipment utilized in long life space applications must achieve a minimal reliability of 0.95 for a ten year time period, [6]. According with this information, the single SBC assembled with military parts must be maintained before 2.44 years, hence does not qualify either as a long life space equipment.

In addition, a reliability study was made for a SQCS architecture assembled with just 2 SBCs. For this architecture a Markov model was obtained, similar to that shown in figure 2.b. For this model, the states F''CR and F''CRR were eliminated. Then the respective Markov equations were obtained, generating a matrix [A] of 5x5 elements. Afterwards, the vector of probabilities to stay at each one of the model states was extracted. Then grouping the SQCS success states the survival reliability was determined. Again, to make the calculation of such a vectors it was elaborated another interactive software in Matlab to generate reliability curves.

Figure 4.a shows the reliability results for three different types of SQCS (each one with 2 SBC) assembled with commercial, military and space qualified components. As can be seen, reliability results for the military version are above 0.95 for 1, 3, 5 and 10 years of operation. This means the equipment accomplishes Hoffman's rule as well as the requirements for long life space equipment. In the case of the commercial version reliability data are: 0.992, 0.966, 0.927 and 0.798 for 1, 3, 5 and 10 years of operation, respectively. In this case only the reliability for 1 year of operation satisfies the Hoffman's criteria. In other words, a commercial SQCS containing two SBC may be used in space for a mission lasting less than one year, if and only if the commercial parts are protected for latch-up phenomena.



(a) (b)

Figure 4. Reliability data for SQCS assembled with two SBC: (a) Three versions of SQCS; (b) SQCS and a single SBC, both of them assembled with military parts.

In figure 4.b reliability results are given for a SQCS (containing two SBCs) as well as for a single SBC, both of them assembled with military parts. The reliability values for the SQCS for 1, 3, 5 and 10 years are all over the Hoffman's criteria. In addition, they all accomplish the reliability indexes for long life space equipments. On the other hand reliability values for the single SBC are the same as those discussed for figure 3.b.

In this way, the obtained results show that SQCS reliability forecast results are encouraging and better than those obtained from centralized computer systems without redundancies.

8 Concluding remarks

This paper has presented the evaluation procedure undergone by the SQCS which was specially designed and manufactured in México for the Satex microsatellite. Taking in to account that SQCS is in charged of critical microsatellite operations, it deserved an architecture design with cold standby spares to avoid single points of failures. In addition, its validation required the availability of complementary satellite subsystems for hardware and software debugging. However all of the satellite subsystems were designed and fabricated in parallel fashion, by this reason the validation of the computer server flight model required the development of special tools. In this sense a satellite simulator, an emulation software for payloads, as well as the earth station software were created to enable SQCS validation without the need of complementary hardware satellite subsystems. In addition, the ESS provided virtual animations facilities to monitor the computer server behavior at a glance. With referred resources the SQCS was debugged in hardware and software, conducting to a successful validation.

In addition, to know the reliability gains obtained from SQCS hardware spares a reliability prediction study was performed. For this purpose, combinatorial techniques, the exponential failure law and the military standard MIL-HDBK217f notice 2 were employed to reduce the SQCS hardware architecture into modules. From these modules the participation of hardware spares were represented by Markov models, and then the Markov equations were obtained. To obtain reliability forecast data dedicated Matlab software was elaborated. The obtained reliability curves show that aggregated redundancies in critical parts of the architecture generate good reliability expectations for the SQCS and therefore for the microsatellite. In particular, the SQCS's reliability results fulfill the reliability requirements established for long life space equipment.

In future papers additional SQCS fault detection facilities will be taken in consideration to generate new Markov models for better understanding of the SQCS behavior under the presence of failures and automatic maintenance. In the mean while reliability data should be considered as optimistic because the SQCS reconfiguration process involves additional hardware neglected in the exposed analysis.

9 Acknowledgements

The authors would like to acknowledge to federal agencies from México, TELECOM and COFETEL who supported the work described in this paper. Besides, acknowledges are given to the Mexican Research Institutions which collaborate in the development of this project, in alphabetic order: CICESE, CIMAT, CITEDI, INAOE, IPN and UNAM.

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