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A Proposed Microsat Open Experimental Platform for Amateur Space Communications Research

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Abstract. An on-orbit, open experimental platform (OEP) that includes a flight computer, a real-time operating system, and other supporting systems will enable new, innovative, space communications, spacecraft software, and flight computer research and experimentation. Access to the proposed OEP will be made available to a variety of investigators to support a range of experiments. An experiments board will identify the proposed projects with the greatest scientific merit and relevance to amateur satellites and amateur radio. The OEP could provide great benefits by stimulating radio amateurs and others to undertake technical investigations that will advance amateur satellites and amateur radio. Most importantly, it will inspire and develop the next generation of scientists, engineers and satellite designers.

Introduction

An on-orbit, open, experimental platform that permits, supports and motivates space communications, spacecraft software, and flight computer research and experimentation by radio amateurs and others will provide a tremendous boost to amateur satellites and amateur radio. For brevity, this concept is referred to here as the Space Communications Research (SCR) Open Experimental Platform (OEP), or SCR-OEP. This proposed project has several objectives:

- Inspire and enable amateurs to "conduct technical investigations relevant to the development of radio technique"[8*] by providing an accessible, on-orbit, experimental platform;
- Foster the creation and maturation of technologies that will facilitate the development of future amateur satellites and amateur satellite missions;
- Expand the pool of radio amateurs capable of and motivated to support amateur satellite missions, whether as software developers, as computer designers, as part of a distributed, collaborative ground station, as financial contributors, or in other beneficial roles; and
- Use scientifically meritorious space communications, spacecraft software, or flight computer research to subsidize the development and launch of amateur satellites.

The SCR-OEP Vision

The proposed SCR-OEP project will make a dedicated, on-orbit, flight computer available to a variety of investigators for space communications, spacecraft software, flight computers and similar research and experimentation. Access to the SCR-OEP will be granted based on factors such as the scientific merit and relevance to amateur radio and amateur satellites of the proposed work. The SCR-OEP will use amateur spectrum and all operations will conform to international and national amateur radio and amateur satellite regulations.

[*] A restatement by the International Amateur Radio Union (IARU) of paragraphs 1.56 and 1.57 of the International Telecommunications Union (ITU) Radio Regulations[9].

Access to the SCR-OEP could be administered by an Experiments Board, which will prioritize proposed projects. Meritorious projects could be granted dedicated use of the SCR-OEP, as well as shared up-link and down-link bandwidth, for a period of time. A selected investigator will upload his or her software into the SCR-OEP and conduct experimentation that will typically involve communication with amateur radio ground stations. The investigator may use his own ground station, or may use a distributed ground station coordinated by the SCR-OEP project. Because the SCR-OEP will be an independent, largely isolated flight computer, experimental software and hardware cannot put the satellite or its mission at risk. As a result, it will support experimental software that may have a greater risk of failure than can be tolerated on a primary flight computer.

Potentially, the SCR-OEP project could subsidize the development and launch of amateur satellites. For example, the development of some or all of the SCR-OEP hardware and software might be funded as part of a Federally funded research project. Furthermore, this research project could potentially help qualify an amateur satellite for a no-cost launch as a government-sponsored payload.

The SCR-OEP project will include:

- A hardware platform, a dedicated, non-mission-critical, flight computer onboard an amateur satellite
- A software platform, based on an inexpensive, readily available, real-time operating system
- Experiments, performed using the SCR-OEP
- Investigators, who will design and conduct these experiments
- An Experiments Board, which will prioritize proposed experiments
- A distributed ground station, a system of coordinated amateur radio ground stations that will support SCR-OEP experiments
- The Project Team, responsible for funding, designing, developing, supporting, and maintaining the SCR-OEP
- External support, potentially justified, in part, by the scientific merit and relevance of some of the proposed research

SCR-OEP Hardware Platform

The SCR-OEP hardware platform will be a dedicated flight computer onboard an amateur satellite. The primary mission of this computer will be to support SCR-OEP experiments. As such, it will be connected to the spacecraft's communications receivers and sensors, permitting experiments to access these data. Likewise, the SCR-OEP flight computer will be able to access the spacecraft's transmitters and actuators, although it may be prudent to enable the primary flight computer to selectively inhibit this access. In a similar fashion, the primary flight computer should be able to reset the SCR-OEP flight computer. Figure 1 below outlines a possible configuration for an SCR-OEP flight computer.

The objective of this configuration is to enable the SCR-OEP to support a broad array of experiments, while simultaneously protecting the spacecraft from the effects of unproven software. Additionally, this configuration will provide an ideal environment in which to test new

or experimental flight software by actually using it to control the operation of the satellite. As a precaution, the primary flight computer could monitor the behavior of experimental flight software running on the SCR-OEP and quickly reacquire control of the spacecraft in the event of undesirable results. Furthermore, the SCR-OEP hardware could provide a backup, in the event of the failure of the primary flight computer.

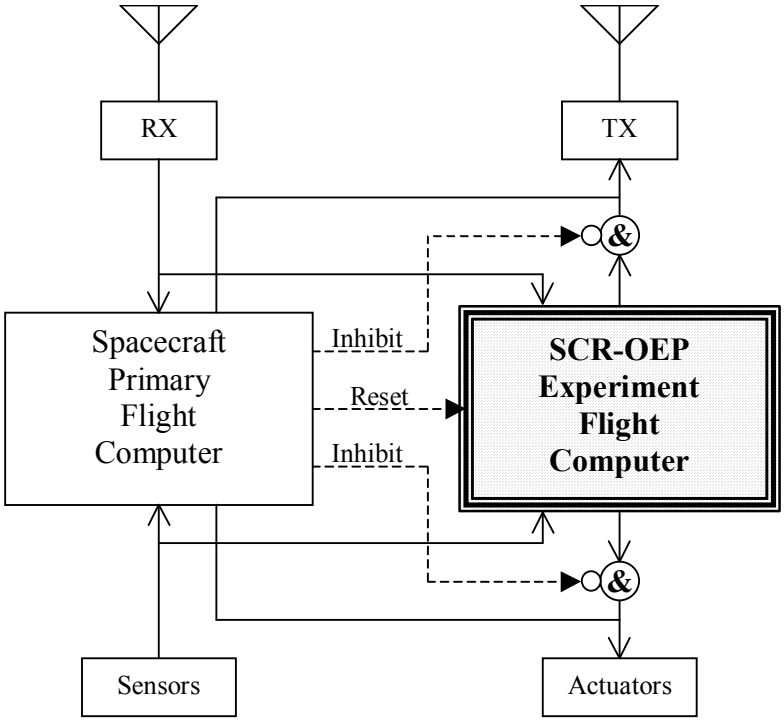

Figure 1. SCR-OEP Hardware Platform Configuration

Many different flight computers could potentially host the SCR-OEP. Of course, a 32-bit, multi-megabyte computer would support a much greater variety of experiments than would an 8-bit, 64-KB machine. A flash memory file system would extend the capabilities of the SCR-OEP by providing permanent storage for software and data, avoiding the repeated upload software or potential loss of experimental data if down-link bandwidth isn't immediately available. A hardware modem would ensure that the processor could communicate reliably after a reset, but digital signal processors (DSPs) would permit experimentation with advanced encoding techniques. The SCR-OEP could use a proven system, such as the SpaceQuest IFC-1000 Integrated Flight Computer[22] being used by the AMSAT OSCAR-E project[5,6,7]. An experimental flight computer, however, would be much more in keeping with the spirit of the SCR-OEP mission. For instance, the SCR-OEP could provide an opportunity for a new flight computer, such as the IHU-3 being considered for the AMSAT-DL P3E project[4], to gain on-orbit experience prior to being flown as a mission-critical component.

SCR-OEP Software Platform

The SCR-OEP will include an operating system and software library, which will permit investigators to focus on developing their own experiments, rather than on creating basic systems

software. An embedded, real-time operating system (OS) is required. An embedded operating system is designed to operate in resource-constrained environments and is often tailored to the specific needs of its host system, while a real-time operating system ensures that interrupts and other time-critical tasks are processed when required. The choice of operating system should maximize the accessibility of the SCR-OEP by potential investigators – an inexpensive, readily available, operating system is needed. This requirement all but demands an open-source operating system, and the need for an embedded, real-time OS (RTOS) further restricts the potential candidates.

The selected RTOS should facilitate the development of experimental software. Investigators, particularly those with limited budgets, should be able to easily run the SCR-OEP RTOS on inexpensive or readily available development systems. Ideally, the RTOS will support Intel x86 processors, as well as the SCR-OEP architecture. This will permit an investigator to develop much of his or her software on a commodity PC, and minimize, perhaps eliminate, the need for access to flight hardware prior to using the on-orbit SCR-OEP. In a similar fashion, the OS should offer an effective software development environment, including compilers for the development system, cross-compilers for the SCR-OEP hardware, good debugging facilities, and other traditional software development tools.

The SCR-OEP systems software will include, beyond an open-source RTOS, a software library that will reduce the effort required to develop software for the SCR-OEP. This library should include:

- Drivers for the peripherals attached to the SCR-OEP flight computer, and stubs or emulators that can substitute for these drivers on a development system
- A flash memory file system
- File transfer software that will enable the up-loading and down-loading of software
- Support for space communications protocols, including the Internet protocols, perhaps the Consultative Committee for Space Data Systems (CCSDS) protocols[2] or the Space Communications Protocols Standards (SCPS) protocols[16], and perhaps even the amateur radio AX.25 protocol.

The operating system selected, enhanced, and used by the SCR-OEP project will provide a modern, mature, space-proven operating system for future amateur satellites. But, the use of this standard SCR-OEP operating system will not be mandatory. Some investigators may wish to use enhanced versions of the SCR-OEP operating system or even experiment with alternative system software. The SCR-OEP will provide a unique, on-orbit host for these projects.

RTEMS

RTEMS (Real-Time Executive for Multiprocessor Systems)[18], an open-source, real-time, operating system, is a strong candidate for the SCR-OEP. It was developed by On-Line Applications Research Corporation (OAR)[19] for the U.S. Army Missile Command in the late 1980s and early 1990s. Since that time, the RTEMS developer community has continued to add features and has ported the OS to numerous architectures and systems. Developers are generally

using the freely available GNU toolset on either UNIX or Microsoft Windows. RTEMS includes:

- A subset of the POSIX 1003.1b (i.e., UNIX-like) applications program interface (API) including threads
- Multitasking support
- Powerful scheduling capabilities
- A port of the FreeBSD TCP/IP stack, including IP, UDP, TCP, ICMP, and DHCP
- Support for several file systems, including an in-memory file system, FAT32, FAT16 and FAT12

NASA Goddard Space Flight Center (GSFC) has ported RTEMS to the Mongoose V flight computer[13] with the intent that it will fly on NASA's Science Technology 5 (ST5) mission[17].

SCR-OEP Experiments

The SCR-OEP is ideally suited to hosting experiments in space communications, spacecraft software, flight computers, and other "technical investigations relevant to the development of radio technique". While a few illustrative examples are included below, investigators will undoubtedly develop a much longer, more creative list when offered a realistic chance to run their software on an Earth-orbiting satellite. Of course, because the SCR-OEP will use amateur radio spectrum, the experiments it hosts must conform to the international and national regulations governing amateur radio and amateur satellites, as is discussed below.

Space Communications. Amateurs have a long history of experimenting with space communications technologies, dating from the first artificial satellite. Examples of research that could be supported by the SCR-OEP include:

- **The use of the Internet Protocols in space communications.** NASA is exploring the use of the Internet Protocols to communicate with near-Earth spacecraft and to enable researchers to access on-orbit experimental data from Internet-attached computers[15]. Opportunities for hand-on experimentation with the Internet protocols in space, such as will be provided by the SCR-OEP, will undoubtedly attract additional members of the Internet generation to amateur satellites and amateur radio.
- **Integration of satellites with digital public safety communications.** Public safety agencies are deploying a new generation of digital radios that use the Project 25 protocols[1]. These protocols specify a 9,600 bps digital channel that includes a 4,800 bps digital voice data stream. SCR-OEP experiments that examine the use of satellite communications to interconnect clusters of digital public safety radios would combine traditional areas of amateur radio activity with cutting-edge satellite and digital voice technologies.
- **Foward Error Correction (FEC) Telemetry Protocols.** FEC techniques developed by Phil Karn have dramatically improved the reception of AO-40 telemetry[10,11]. Extensions of this work could further improve communications with amateur satellites.

Spacecraft Software. The extensive, on-orbit experience with RTEMS gained by the SCR-OEP project will provide future missions a space-qualified, open-source RTOS. Some SCR-OEP

experiments might examine, based on real-world experience, the strengths and limitations of RTEMS as a spacecraft operating system.

Flight Computers. Spacecraft designers, by necessity, are very selective in the risks that they accept when developing a spacecraft or mission. Relying upon an unproven flight computer is a risk that most designers are unlikely to accept unnecessarily. The SCR-OEP, however, will offer a rare opportunity for innovative, and potentially risky, flight computer designs to gain flight experience.

SCR-OEP Investigators

Three classes of investigators will use the SCR-OEP for experiments.

- Outside Investigators, who will propose experiments and may be granted access to the SCR-OEP for a period of time by the Experiments Board
- The SCR-OEP Project Team, which will support the SCR-OEP and will undertake investigations that are intended, in part, to attract external support for the SCR-OEP project
- The sponsoring agency, which may be granted access to the SCR-OEP in return for support

The SCR-OEP will be an *open* experimental platform; it will be available to potentially any investigator with a meritorious proposal. Outside investigators do not need to be members of the Project Team or otherwise associated with the project. Presumably, most of the investigators will be radio amateurs. Some may be pursuing a personal interest in space technologies, some may be students, and conceivably some may be researchers in their professional lives.

SCR-OEP Experiments Board

An Experiments Board will administer the portion of the SCR-OEP time available to outside investigators. Potential investigators will submit proposals describing their desired use of the SCR-OEP. The Board will prioritize the proposed work, based on scientific merit, relevance to amateur satellites and amateur radio, and perhaps other factors. It may also provide guidance on the use of the amateur spectrum and perhaps provide coordination between proposed experiments. Ideally, the Board will include expertise in amateur satellites, small satellites, amateur radio and relevant technologies and research.

The Project Team and the sponsoring agency will be responsible for allocating the other two blocks of SCR-OEP time. The allocation of time between outside investigators, the Project Team and potentially a sponsoring agency is a topic for further study.

SCR-OEP Distributed Ground Station

A virtual ground station, composed of a system of coordinated, geographically distributed amateur radio ground stations, will support SCR-OEP experiments. This system will use the Internet to interconnect participating ground stations and to provide service to investigators. The distributed ground station will enhance access to the SCR-OEP, by permitting investigators without ground stations to conduct experiments on the SCR-OEP. It will also ensure that the

SCR-OEP is used more productively than if every investigator is responsible for communicating directly with the satellite. For example, the distributed ground station will minimize the time required to upload new software to the SCR-OEP by handing off upload responsibility between ground stations as the satellite orbits.

SCR-OEP Project Team

The Project Team will be responsible for the design, development and operation of the SCR-OEP. They will also assume much of the burden of obtaining funds for the project. The team will include a researcher whose mission is to obtain Federal support to subsidize project. Like any satellite project, the SCR-OEP will require the talent and expertise of a large team. Other responsibilities of the Team will include:

- Support outside investigators in their use of the SCR-OEP hardware and software platforms by providing documentation, consultation and mentoring
- Coordinate the creation of the distributed ground station
- Sponsor Investigators' Meetings, where investigators, potential investigators, and others can share their experiences and learn from others
- Publicize the plans, status, successes and experiences of the SCR-OEP project to the amateur satellite community, radio amateurs, potential outside investigators, potential sponsors, and the general public

Opportunities for External Support

The development and launch of amateur satellites are *very* expensive undertakings. Finding new ways to support these activities is critical to the continued success, perhaps even existence, of our hobby. The SCR-OEP will provide an opportunity to further explore two long-standing, although perhaps not widely used, sources of external support for amateur satellites: Federally funded research projects and government-sponsored launch opportunities.

Federally Funded Research

The SCR-OEP on-orbit experimental platform will be fully capable of hosting "real science", scientifically meritorious research and experiments of the quality expected of professional researchers or Federally funded research projects. The following examples include research projects that could have used the SCR-OEP, if it had been available, or topics from recent Federal research solicitations that could easily benefit from the SCR-OEP.

- **Space Communications Research.** Some of NASA GSFC's IP-in-space experiments were conducted on a flight computer onboard UoSAT-12, known in amateur circles as UO-36[20,21]. These experiments could easily have been performed on the SCR-OEP, if it had been available. The latest NASA Small Business Innovative Research (SBIR) solicitation includes a request to create "Internet-based protocol modules and architectures that will provide seamless network continuity between terrestrial and aerospace-based platforms and environments"[12]. Not surprisingly, this topic is similar in concept to the SCR-OEP distributed ground station.

- **Spacecraft Software Research**. NASA has explored the use of open source, real-time operating systems, including the FlightLinux project, which examined the potential use of RTLinux, a real-time variant of Linux, as a flight operating system[14]. The SCR-OEP will provide an opportunity to gain flight experience with an open-source RTOS, perhaps RTEMS.

- **Education and Outreach.** NASA's mission is, in part, "to inspire the next generation of explorers ... as only NASA can". The Amateur Radio on the International Space Station (ARISS) project has been highly successful in inspiring countless school children – and apparently not a few adult radio amateurs as well. Earlier this year, the Air Force's top two space officials told a Senate subcommittee that the development of a "space cadre" was one of their top priorities[3]. It is hard to imagine anything more inspiring or educational for a student than to conceive, propose and conduct an experiment on an on-orbit flight computer hosted by an Earth-orbiting satellite. The SCR-OEP project would be an ideal candidate for providing these opportunities.

Conceivably, portions of the SCR-OEP project, such as the development of the flight software, the flight computer or the distributed ground station, have enough scientific merit to justify the award of Federal research funds. Of course, the only way to know for sure is to offer Federal agencies an opportunity to fund this work by submitting research proposals.

Government-Sponsored Launch Opportunities

The Department of Defense (DoD) Space Test Program (STP)[24] "provides spaceflight for qualified DOD sponsored experiments at no charge to the experimenter, via the DOD Space Experiments Review Board" (SERB)[23]. The SERB evaluates the "military relevance and technical merit" of the proposed experiments. The SERB Web site states that "DOD experiments normally originate in the Service (Army, Air Force, Navy, NASA) laboratories or research institutions (colleges, universities, think tanks, etc.) but are in no way limited to these institutions." Clearly, competition for free space launches is very intense. Nonetheless, the Naval Postgraduate School and the Air Force Academy have successfully used this process to launch their student satellites[25]. Certainly, the hurdles are very high and the competition is very fierce, but the potential rewards are so great that the amateur satellite community would be remiss if it didn't aggressively pursue this opportunity

SCR-OEP and Amateur Spectrum

The SCR-OEP will use amateur satellite spectrum and its operation will be consistent with the international and national regulations governing amateur radio and amateur satellites. Radio amateurs will be the primary users and beneficiaries of the SCR-OEP project. Many of the investigators will be licensed radio amateurs, as will be all of the satellite ground station operators. The SCR-OEP experimental platform is expected to be hosted by and help support an amateur satellite and the technologies developed by this project are likely to benefit future amateur satellites.

International Amateur Radio Union (IARU)

The International Amateur Radio Union (IARU) coordinates the use of amateur radio spectrum by amateur satellites. Their "Amateur Radio Satellites: Information for Developers of Satellites Planned to use Frequency Bands Allocated to the Amateur-Satellite Service" contains a wealth of useful information[8]. It contains the IARU's highly relevant interpretation of the phrase "technical investigations ... [of] radio technique" in the International Telecommunications Union (ITU) Radio Regulations[9]:

> *Development of "radio technique" means having a reasonable possibility of application to the development of radio communication systems.*
>
> *Examples of technical investigations relevant to development of radio technique include, but are not limited to:*
>
> - *operational analysis of protocols for digital voice and data communication ...*
> - *development of spacecraft computers, memory, operating systems, programs, and related items ...*

Clearly, the potential topics of SCR-OEP experiments listed above, space communications, spacecraft software, and flight computers, fall within the IARU's guidelines. Of course, proposed experiments that fall outside these areas should be evaluated against the IARU guidelines and ITU and national regulations.

The IARU also states that experiments using amateur spectrum should be open to all amateurs.

> *All telecommunication facilities, except space telecommand, operating in amateur-satellite service allocations should be open for use by amateur radio operators worldwide. All experiments utilising frequencies allocated to the amateur-satellite service should be freely available for use by radio amateurs worldwide and for reception by students and educators.*

The SCR-OEP gives new meaning to the term "open" by permitting investigators unaffiliated with the project to execute their own software on an on-orbit flight computer hosted by an amateur satellite.

The preliminary, informal, and undoubtedly incomplete analysis of the SCR-OEP's use of amateur spectrum presented here should be supplemented by a more detailed examination by experts with experience in this area.

Potential Benefits for Amateur Satellites

Attracting and inspiring the next generation, developing new amateur satellite technologies, and expanding sources of support for amateur satellites are just a few of the benefits that will result from a successful SCR-OEP project.

Attract, Inspire, and Develop the Next Generation

The SCR-OEP project will attract, inspire and develop the next generation of scientists and engineers, radio amateurs, and satellite designers, builders, and operators. It will enable future satellite designers and builders to gain hands-on experience developing software for amateur satellites, an opportunity previously available only to a small group of highly qualified individuals. This project will also enhance communications between the amateur satellite community and those building student and academic satellites.

Develop New Satellite Technologies

The SCR-OEP project will develop new technologies applicable to amateur satellites. It will develop and mature a modern RTOS for amateur and small satellites. This RTOS offers the promise of a de facto standard for small satellites, enabling flight software to more easily be reused between satellite projects and perhaps even terrestrial amateur radio projects. Direct Internet access to orbiting amateur satellites will offer new ways to publicize the accomplishments of amateur satellites.

Expand Sources of Support for Amateur Satellites

Perhaps the biggest contribution of this project will be to develop new sources of support for amateur satellites, specifically Federal research funds and government-sponsored launches.

Making Proposed SCR-OEP Fly

The proposed SCR-OEP concept is currently just that, a concept. Translating this concept in to a real, on-orbit, experimental platform is a major undertaking. The following small, first steps will provide a solid foundation for a highly successful SCR-OEP project.

- Review and discussion within the amateur satellite and amateur radio communities will help refine and strengthen the SCR-OEP concept.
- Evaluation, feedback, and particularly formal support by the AMSAT Board of Directors will considerably improve the likelihood of its success.
- Creation of one or more research proposals will potentially help obtain funding and even a government-sponsored launch.
- Further investigation of the use of amateur spectrum by licensed radio amateurs supported indirectly by Federal funds or government-sponsored launches will help ensure that this project operates consistent with international and national radio regulations.

The SCR-OEP concept proposed here, combined with a tremendous amount of hard work and not a small amount of luck, could offer a means to attract new participants to the amateur satellite community and support the construction and launch of additional amateur satellites.

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