Rascal: Sensing and Navigation for Space Situational Awareness

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Introduction. Space Situational Awareness (SSA) is an important capability for the Air Force. Encompasses a broad range of capabilities. We are interested in detection, characterization and proximity operations.

One of the many challenges in SSA is the ability to detect the presence of another space object at range (30+ km). Imaging at that range requires very narrow-field-of-view optics to gain sufficient resolution, which prevents passive ("all-sky") detection.

The University of Michigan's RAX-2 CubeSat measured Received Signal Strength Indication (RSSI) in the UHF band during the first week after ejection. The plot of RSSI over time (Figure 1) indicates that there was higher-than expected RSSI during the first few days after ejection.

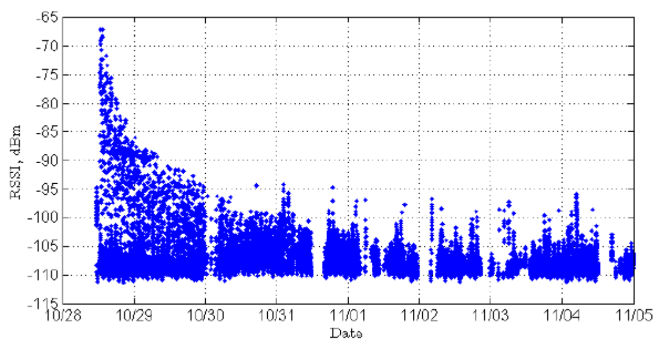

Figure 1. RSSI for RAX-2 in the UHF Band for the First Week Post-Ejection (from Springmann, Kempke, Cutler, "Initial Flight Results of the RAX-2 Satellite", 26th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2012, paper SSC12-XI-5)

Given that RSSI varied from -112 dBm up to around -90 dBm during those days, we suspect that most of the high points of the exponential decay were due to on-orbit RF emissions (which is of limited value in SSA). However, we cannot rule out induction from ground emissions (especially in the first few hundred meters). Therefore, we want to perform a more controlled orbital experiment using RSSI and infrared imagery. While we are performing the RSSI evaluation, we will evaluate the usefulness of infrared and visible imagery for closer-range SSA applications.

Mission Objectives.

1) The primary mission of Rascal is to <u>quantify the effectiveness of RSSI for spacecraft detection</u> at three frequency bands at ranges from 10 meters out to 100 km. We are interested in quantifying the maximum range of detection for both passive and actively broadcasting spacecraft. This will take place in three phases:

   a. **Minimum Success** consists of collecting RSSI data during the separation of two known spacecraft from initial separation to 100 km relative drift. The spacecraft will have times of passive operations and active RF emissions. This timed data will be matched to orbit information to correlate separation distance with RSSI.
   b. **Complete Success** consists of actively maneuvering one spacecraft from an initial distance of greater than 100 km to a sufficiently close distance that RSSI measurements detect the presence of the other spacecraft in both passive and active RF modes.
   c. **Extended Success** will occur if the objects naturally drift within detectable range (which could occur every 6-12 months, depending on initial conditions) and are detected by RSSI.
2) The secondary mission of Rascal is to <u>quantify the effectiveness of other sensor technologies for proximity operations</u>, specifically the use of long wave infrared (LWIR) and visible imagers.
   a. **Minimum Success** consists of observing the separation of two known spacecraft and their relative drift in these wavelengths out to the maximum observable distance. (Certainly much less than 100 km.)
   b. **Nominal Success** consists of characterizing the observability of surface features and their minimum angular resolution.
   c. **Complete Success** consists of collecting additional data during the rendezvous portion and positively identifying both the presence of the other spacecraft at range and then identifying one feature (e.g. the imager of the other spacecraft).
3) The tertiary mission of Rascal is to demonstrate the capability of imaging systems and R134A-based propulsion systems for proximity operations.
   a. **Minimum Success** consists of intentionally returning the two spacecraft within 10 km of one another.
   b. **Complete Success** consists of bringing the spacecraft within 100 meters of one another and staying within that distance for at least one orbit.
4) As volume, mass and power allow, additional payloads will be carried aboard Rascal. These would be activated after the attempted rendezvous portion of the Rascal mission and operate as long as on-board systems and orbit allowed. For example, we would likely fly another version of the Independence payload developed by Vanderbilt for our Argus mission.

System Description. A team of aerospace engineering students working on their senior design project will perform a complete Phase A study of the Rascal mission during the Fall semester. (These students have contributed to the Argus and COPPER missions as hardware integrators and test leads.) Therefore, the following description should be considered as preliminary; it is provided to show that a feasible design point exists.

The nominal design consists of a 6U-class system launched as a secondary into any high inclination orbit; as a nominal case, 40° inclination, 500 km circular is used. The 6U system is actually two independent 3U spacecraft fastened to a baseplate which acts as the tab/base structure for the 6U dispenser. The spacecraft are identical, with subsystems as shown in Table 1. These baseline components were chosen because of the experience that the SSRL team has had with those systems.

Each 3U spacecraft will consist of a core spacecraft bus based on the SCARAB bus developed by SSRL for its first two missions (COPPER and Argus): CDH, Power, and Comm. These components will fit in the center "1U" of the 3U spacecraft, along with the other two mission radios and the separation mechanism keeping the 3U spacecraft attached to the baseplate. The bottom 1U will be for the cold-gas 6DOF propulsion system, based on the Bandit design from previous University Nanosat competitions, but taking advantage of the lessons learned from the RAMPART mission that will fly an additive-manufactured, R134a-based propulsion system on ORS-3 in Q3 2013. The upper 1U will be for the imaging systems and ADCS actuators.

Table 1. Notional Spacecraft Components for Rascal 3U. As noted above, the complete trade studies and final component selection will take place in the Fall semester and bridging into the Spring

Subsystem	**Notional Component(s)**	**SSRL Experience/Heritage**
ADCS / Nav	Rate gyros Reaction wheels GPS unit	COPPER, Argus - -
CDH	CubeSat Kit PIC24-based system Salvo RTOS	COPPER, Argus COPPER, Argus
Power	Clyde Space 3U EPS Clyde Space Lithium Battery Spectrolab UTJ body-mounted solar cells	COPPER, Argus (1U version) COPPER, Argus COPPER, Argus
Comm	AstroDev Helium UHF/VHF transceiver AstroDev Lithium transceiver HF receiver	COPPER, Argus - (flown on RAX-2, others) -
Structure / Mechanisms	CubeSat Kit 3U Structure TiNi ERM-500 Release Mechanism	COPPER (1U), Argus (2U) -
Thermal	Passive	-
Propulsion	R134a-based 6-axis propulsion system Additive-manufacturing propellant tank/plumbing	Bandit - (will fly on RAMPART)
Imaging	Flir Tau 320 LWIR imager COTS visible camera	COPPER -

Concept of Operations. Rascal consists of a pre-launch phase (Phase 0) and four on-orbit phases.

Phase 0 (pre-launch): During the Nanosat-8 development cycle, the we will collect post-separation RSSI data from other flight missions. The same AstroDev systems used to collect RSSI on RAX-2 will fly on COPPER, Argus, PrintSat, RAMPART, Aeneas and doubtlessly other missions as well. We will contact those teams and ask that they collect RSSI during the first few days after launch. (We can at least expect the COPPER and Argus teams to cooperate!) This will provide us with additional flight data using Rascal's baseline radios, albeit without the level of calibration we will have with Rascal. The ORS-3 mission provides a great opportunity to get correlated data, as COPPER, PrintSat and RAMPART (at least) will be capable of collecting the desired RSSI measurements.

Also during Phase 0, we will perform detailed anechoic chamber tests using the Rascal 3U spacecraft both attached to and separated from the baseplate, enabling us to calibrate the expected RSSI performance. At the end of Phase 0, Rascal will be integrated for secondary launch using a 6U dispenser.

Phase 1 (launch vehicle ejection/checkout – two weeks): Immediately after ejection from the launch vehicle, on-orbit, Rascal will collect RSSI data in all three bands, continuing to do so for the first week. We will check the RSSI levels against the expected/known behavior of other systems released on that launch vehicle. The combined spacecraft will be detumbled and all systems tested. This phase continues until all RSSI measurements have dropped to a low, quasi-steady-state level indicating that the system is far from all other space objects (nominally 2 weeks).

Phase 2 (controlled separation/baseline mission success – two weeks): At the start of this phase, one 3U is released from the baseplate and allowed to drift away (nominally at a few centimeters per second). Each spacecraft will perform a detumble/slew maneuver to fix its imagers on the other, observing continuously as the two systems drift out of range. RSSI measurements will be continuously collected. The RSSI data will be collected in three specific functional modes:

1) Fully passive. Neither spacecraft will broadcast, nor will their be active ground contacts.
2) Active in-space. Each spacecraft will broadcast a low-power UHF/VHF beacon at regular intervals. (One spacecraft will beacon in UHF, one in VHF.)
3) Active from ground. When passing over SSRL ground stations, the ground will broadcast a high-power “ground beacon” in UHF, VHF and HF. The data will be observed

Also during this phase, short, zero-net thrust bursts of R134a will be released at known intervals by each spacecraft to be observed by the other.

Table 2. Rascal Mission Phases

Phase	Key Events
0 (pre-launch)	Collect RSSI/orbit from other missions Calibrate in anechoic chamber
1 (launch sep)	Launch sep / RSSI collection Detumble / checkout Ground beacon calibration
2 (3U release)	Release of 3U and drift to > 100 km RSSI collection (passive, beacon, ground) Imager observation Propellant firing
3 (rendezvous)	Maneuver from >100 km to 100 m RSSI collection (passive, beacon, ground) Imager observation Propellant firing
4 (extended)	Release/observe baseplate Activate backup payloads

Phase 3 (rendezvous/complete mission success – four weeks). When the two spacecraft have reached sufficient distance, one spacecraft will be commanded to activate its propulsion system to automatically maneuver to rendezvous back within a 100 meter proximity of the other spacecraft. The “sufficient distance” is nominally 100 km, but this distance could be increased or (more likely) reduced based on the performance of the various sensors and navigation systems. During the rendezvous portion of Phase 3, the RSSI and propulsion observations conducted in Phase 2 will be repeated. After the spacecraft are returned within 100 meters for at least one orbit, the separation and rendezvous phases may be repeated to provide additional data-collection opportunities.

We recognize that this Phase carries significant risk, since orbit rendezvous from these distances has not been demonstrated for CubeSat-class spacecraft. (In fact, CubeSat rendezvous is part of a $15M NASA Edison mission.) We have included Phase 3 because active, controlled rendezvous provides additional calibrated data-collection opportunities for our primary mission. We will mitigate this risk by including GPS receivers and communications crosslinks on each spacecraft, allowing navigation data sharing to improve relative performance. More importantly, Phase 3 is not necessary for minimum mission success, and thus eliminating Phase 3 is a descope option.

One of the critical activities of the senior design team will be to perform a detailed risk/mitigation analysis of Phase 3, including options such as elimination of the Phase and moving some elements into Phase 2 (such as attempting rendezvous from 50 meters, 100 meters and 1 km before drifting out to several hundred km).

Phase 4 (extended operations – 3+ months): Once Phase 3 has been completed (or we have given up trying to complete Phase 3), Phase 4 begins with releasing the second spacecraft from the baseplate, providing another metallic object for RSSI and imaging SSA sensing. The objects all drift away from one other while data is collected. If mass, power and data management allow, simple tertiary payloads will be added to each Rascal 3U spacecraft and activated in this Phase. (Our first candidate will be Vanderbilt's Independence radiation-effects modeling payload that we already are flying on Argus.) Alternately, we will open up each Rascal 3U's two UHF/VHF transceivers (and HF receiver) for Amateur radio service.

If both Rascal systems operate for sufficiently long (6-10 months), their relative orbits will naturally bring them within a few hundred kilometers (or closer). We will continue to collect RSSI and imaging data whenever the paths intersect sufficiently.

Phase 4 ends at either on-board failure of a critical subsystem, the tertiary payload operators choose to suspend operations, or the spacecraft deorbits. In all cases, all space elements will be designed to passively deorbit within 25 years of the end of the mission.

Military Relevance. We are still working towards letters of support for military relevance. At the moment, we have identified the following Space Scholars topics from 2012 that are directly related to this work:

- Advanced Guidance Algorithm Development (Dr. Morgan Baldwin)
- Computer Vision for Relative Navigation (Mr. Nathan Stastny)
- Dynamics and Control Solutions for Spacecraft Translational and Rotational Maneuvers (Dr. Josue David Munoz)
- Pose Estimation (Dr. Seth Lacy)
- Satellite Guidance, Navigation, and Control Applied to Close-Proximity Missions (Dr. Thomas Alan Lovell)

SSRL Team. This work would be conducted by students and faculty at Saint Louis University in the Parks College of Engineering, Aviation and Technology. Students would participate for course credit at the senior and sophomore levels, as volunteers and as paid summer interns. It is anticipated that at least two MS-level theses and one PhD dissertation will be based on the work developed under this proposed mission.