Deployable multi panel solar array for low cost 1U cubesat missions

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Abstract

During the mission design for the first Ecuadorian satellite, the NEE-01 PEGASUS, the need arose for having a power supply in order to charge our large battery banks; Calculations shown that we will need no less than 40 of our solar cells. The team of the EXA began studying the design and development of thin, deployable, multipanel solar arrays, able to fold in no more than 6 millimeters height as our spacecraft was an 1U cubesat design and the restrictions allowed a maximum clearance of 6.5 millimeters. Once in orbit each array will deploy to 3 panels each, measuring 27 centimeters by 8 centimeters wide with a total of 57 solar cells for a maximum of 14.25 watts of power generation capability.

The result was a device with no compound hinges for release and deploy that met the mission requirements and surpassed them; After much testing and trials they were own and successfully operated in NEE-01 PEGASUS and NEE-02 KRYSAOR, after more than 3 years in space, the arrays keep providing enough power to run the payload at full capacity. A new version of this array will flight in two upcoming U.S. cubesat missions in 2017 and 2018 and the upcoming missions for this program.

This paper will describe the development and testing of this array in the PEGASUS missions as well as the upgraded design for the new mission in 2017.

1. BACKGROUND:

EXA is the Ecuadorian Civilian Space Agency, a civilian NGO created in 2007, in charge of the administration and execution of the Ecuadorian Civilian Space Program – ECSP(1).
As part of the ECSP, Project PEGASUS was developed to demonstrate indigenous satellite building, testing and operation capabilities and to this end a ground station called HERMES-A(2)(3)(4)(9)(11) was built and tested successfully from 2009 to 2013 and 2 satellite flight models were also built in house, tested and launched successfully, both satellites are still in operation at the time of writing this paper.

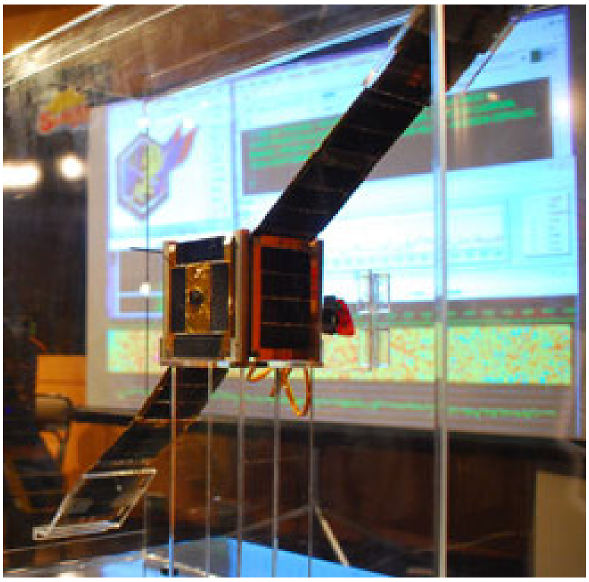

Fig-1.1 The NEE-01 PEGASUS in orbital flight configuration with its 2 DSA Multipanel solar wings deployed during its maiden presentation on April 4, 2011

NEE-01 is the Ecuadorian registry number meaning 'Ecuadorian Space Ship – 01' in Spanish, so the first spacecraft was christened **NEE-01 PEGASUS,** launched on April 25, 2013(19) and the second one was christened **NEE-02 KRYSAOR,** launched on November 21, 2013(30), both satellites were NEE-class spacecrafts as we named this architecture.

The design and development team was led by Ronnie Nader and composed by Sidney Drouet, Manuel Uriguen, Hector Carrion, and Ricardo Allu(23)

2. DESIGN CRITERIA:

The NEE-class satellites were designed as a 1U cubesat form factor, however, as soon as the initial design was complete, a limitation was discovered in the power budget calculations: A lack of space for enough solar cells, so we decided to add a pair of multi-panel solar arrays(22) or 'wings' to address this deficiency. This solution required the use of big batteries, bigger than any battery array ever built or available for a 1U cubesat and even for bigger cubesats (44). Using the low cost, low efficiency solar cells that we could afford within the budget limitations of the program, calculations shown that we would need at least 21 of this cells in each 'wing' to form 2 solar arrays capable of providing at least 5.25 J/sec, this being coupled with our power storage of 4 battery banks with a total capability of 106.56 Watts, the challenge was to pack this many cells power into an space small enough to fit into a 1U structure within the limitations of 6.5 mm in folded configuration.

Many challenges arose from these requirements:

- **A.** Locate solar cells of the right geometry of length, width and thickness to fit into a 83mm by 90mm titanium scaffold with a maximum thickness of 0.25 mm for a maximum rise of 1.5 mm per panel and a fold total thickness of 4.5 mm for the 3 panels
- **B.** Locate solar cells of the maximum possible energy density, constrained by the right geometry and at an affordable price.
- **C.** A release/deploy method able to free the panels and extend them into final position that will not compromise the 4.5 mm thickness limit and can be actuated thermally and/or electrically and will not create whiplash.
- **D.** An affixing technique that can withstand thermal vacuum and yet maintain structural integrity.

E. A dependable and safe flat circuitry path enough to resist thermal vacuum and withstand degradation due to space environment effects while maintaining a good degree of conductivity/low resistance.

3.TESTING AND MANUFACTURING:

We were able to locate solar cells, space grade, glass covered in the U.S. that met the specifications required by conditions A and B:

Length: 62 mm.
Width: 22 mm.
Thickness: 0.45 mm.
Volts: 0.5 V
Current: 0.5 A

We connected them in series to increase the voltage while maintaining the current enough to activate the regulators that will stabilize the array power output to the EPS power bus, each face of the array will be considered as an input channel, therefore each wing actually represents 2 solar arrays, side A and side B, which in turn will connect to its own diode/regulator circuitry in the main EPS board for a total of 8 power channels inputs.

At this point we had solved A and B conditions, however, conditions C, D and E remained unsolved; We solved condition C using NiTiFe super elastic/thermal fibers so both the superleasticity and the thermal activation properties will help in the deploy of the panels and used passive NiTi bars to solve the release problem. Condition D was solved using space grade epoxy 3M 2216 B/A amber over the polyimide skin over the titanium scaffold to affix the cells and condition E was solved using polyimide/copper flexible circuit paths.

Fur solar arrays were manufactured, two for the NEE-01 and 2 for the NEE-02, after many hours of testing and tinkering we were able to tune the deploy/release assembly to our needs and the arrays where integrated into the satellites..

However there was one difference between them: in the NEE-01 the release mechanism was 2 NiTi activated by solar heat, and in NEE-02 the release assembly was active, powered by an auxiliary battery this difference was due our experience in the first satellite as we observed a longer than expected time for the passive release technique to work, mostly due the initial tumbling state of the satellite and fortunately our huge battery banks were enough to power the satellite until the sun heated the bars enough for them to release the solar arrays. We did not want to repeat the experience or incur in unnecessary risks for the second satellite, so we added heating coils to the release bars this time, and the technique worked flawlessly after some tests and tuning and actually in orbit, the release occurred within a few minutes of the second satellite being released into orbit.

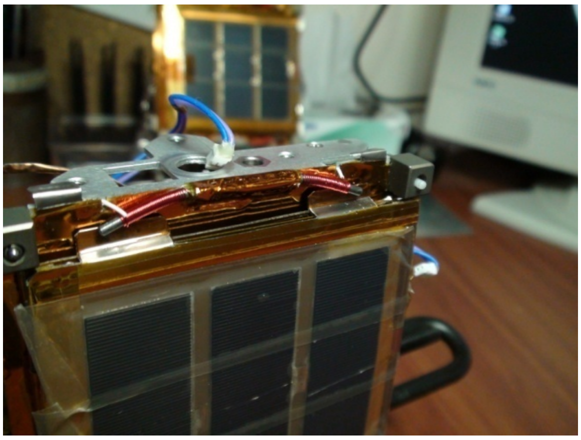

Fig-3.1 One of the active release NiTi bar assembly installed on the NEE-02 KRYSAOR showing the heating coils.

3.1 In-Orbit Testing:

The first satellite, the NEE-01 PEGASUS was launched on April 25[15][18] on a LM2D Chinese vector and worked properly[21] until an in-orbit anomaly with an unknown object caused the spacecraft to lose attitude control[26][27][28][31][32], damaged one of the deployable solar arrays and deformed the main antenna, the satellite survived the event, but remained out of contact and without attitude control for about 6 months until we were able to recover the signal[26][34][37][40], but an attitude control loss also meant that the satellite could not charge the batteries as it could not point the large solar arrays properly to the sun, so the batteries were actually depleted. Surprisingly for everyone, once the satellite could regain attitude control, the batteries started to charge again, although the antenna damage remained, the spacecraft continued transmitting the beacon as our EPS included a feature that allowed the system to operate on solar power only in the event of the batteries to get depleted beyond recharge. With the solar arrays being so large, the collected solar power was enough to power the whole satellite during this period until the batteries recovered.

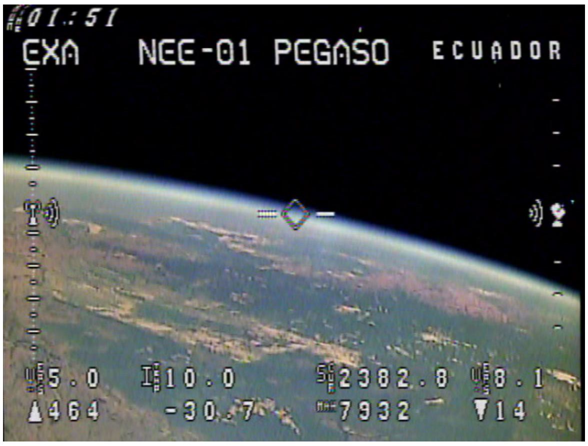

Fig-3.1.1 A snapshot of the first public video transmitted by the NEE-01 during May 16 2013, 10h41m pass over South America

At the same time, the satellite operating on solar power provided the electronics waste heat needed to prevent the batteries from freezing thanks to the thermal transfer bus system thus greatly contributing to the battery life and ulterior recovery.

This unintended and harsh test of our solar arrays showed how the rugged engineering worked in ways that we did not foresee at the time of design and build, however, the design guidelines proved successful in arresting problems as serious as the ones we faced during this anomaly.

4. THE NEW DSA GENERATION:

In March 2016, the EXA was selected by the Irvine Cubesat Stem Program[14], a U.S. Public schools based satellite program comprising twelve 1U cubesat launches among 14 years to provide the Deployable Solar Arrays (DSA), titanium infrastructure, NEMEA shielding and battery arrays for this program, the maiden launch of IRVINE01 is to take place in June 2017 to a sun-synchronous orbit. For this specific need we were asked to design a new class of battery array to go in line with a new class of DSA, the new array was designed with the same principles as the original arrays but scaled down to 20Whr of capacity an only one side of the PCB populated with cells and this side had only 6 cells instead of 8.

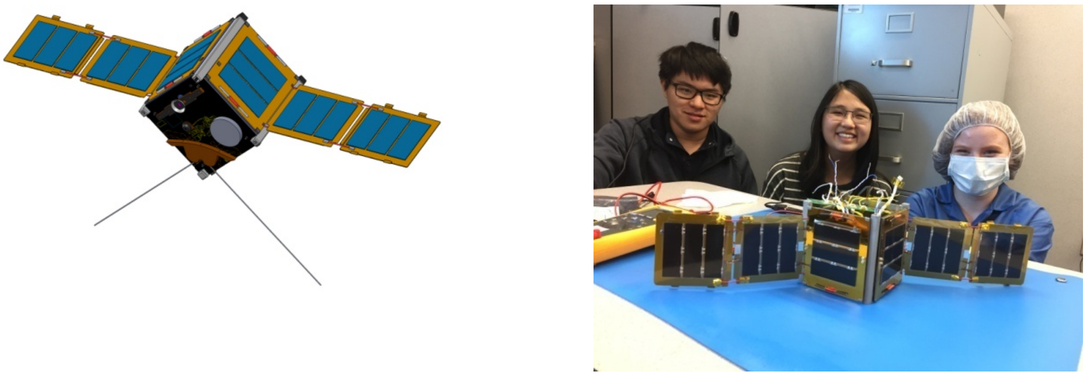

Fig-4.1 IRVINE01 final design showing the scaled-down DSA arrays in deployed configuration and ICSP students integrating the actual DSA built for the spacecraft.

This new design included many new features that in fact were born from a wish list that arose from the experience with NEE-01 and NEE-02 satellites:

Active release system tuned to lower energy usage
Active deploy system designed for low energy and high tensile strength
Passive contact sensors for release and deploy operations
PCB integrated circuitry and SMD diodes
Standard Molex pico-blade connectors grouped by function.
Reduce the array weight to less than 150 grams per array.

All these objectives were accomplished in the final production design and test showed that the new DSA design was even more efficient than the original models already in orbit. This new DSA solar arrays were fitted with a compact magnetorquer design called MT01 on the side walls and also equipped with the NEMEA MLI shielding[13] and affixed to the space craft structure with titanium clips.

5. THERMAL KNIFE VS. ARTIFICIAL MUSCLES:

The well known and proven thermal-knife technique was originally developed in the 60s and while it has been tried and true, mission after mission it presents many problems:

- The assembly needs to be rebuilt each time a test is completed.
- The assembly needs burning resistances and fishing lines, and it uses a lot of power.
- If it fails in orbit, you cannot try again. (End of Mission)
- If the electrical circuitry fails there is no fallback method to activate it. (End of Mission)
- If it is successful, it will normally imprint the spacecraft with a whiplash counter movement that complicates attitude determination calculations and processes.

Even when this technique is simple, it has not changed in more than 50 years and presents problems and inconveniences that we were challenged to overcome. The answer was to develop a new technology based on shape memory alloys, and encouraged by the results achieved in our previous experiences in orbit we decided to develop this technology further to the point of maturity, the advantages are:

-Can be tried as much as 10.000 times during testing or operation.
-Nothing to be replaced after each test or operation.
-Very easy to install or remove
-Only power needs to be applied to be operated.
-Power consumption is lower than TK
-If it fails in orbit, you can try again.
-With its gentle, controllable operation, it does not disturb the satellite’s attitude.
-If the electrical circuitry fails, eventually the heat of the sun will deploy the muscles in a few orbits (tested in lab, in orbit and in thermal vacuum)

The Cons however are:

-They are difficult and tedious to manufacture.
-It is delicate to tune them to the precise parameters.
-The research needed to achieve the best parameters is long and complicated.

Our evaluation was that even with the cons noted above, it was worth the effort invested to develop a new, state of the art deploy/release technology that opens the door to multiple applications.

Then, a new class of artificial muscles were developed for the new DSA generation, the MDR/R1C model was designed to serve the release assembly in order to ensure the panels will not come out loose during the launch phase of the mission, these were made from NiTi 2 mm diameter bars as the original DSA in NEE-01 and NEE-02, but equipped with a more efficient heating coil in order to reduce both time and energy use.

The MDH/R2 model was designed for the deploy operation in order to move the panels in place once the release operation completed successfully, this were made from NiTi alloy using a proprietary 2 dimensional configuration to avoid the problems related to metal fatigue and shape deformation over time.

The MDH/R2 artificial muscles are capable of lifting a weight of 50 grams each or 75 times its own weight, the MDR/R1C artificial muscles are capable of pushing 80 grams or 120 times its own weight, each DSA has 4 MDH/R2 and 2 MDR/R1C.

Two videos of the deploy and release operation are publicly available on Youtube:
https://www.youtube.com/watch?v=zP_ONUQfIZs
https://www.youtube.com/watch?v=kNMimYQLZck

5.1 Final Parameters:

Supply Voltage: 4.5V to 5.2V top side and 3.2V to 3.V bottom side
2A@20V Schotky diodes integrated
Power delivered for full sunlight in LEO: 3.75 W minimum, 4.2W maximum
Cell Efficiency: 19% (low cost)
Release in 19 seconds using 152 joules
Deploy in 8 seconds using 51 joules
Mass with NEMEA shielding: 115g
Panel Thickness: Folded: 5.5mm, Unfolded: 1.5 mm
Operating Temperature: -80 to +130°C
Radiation Tolerance: 2 years minimum in LEO, 4 years minimum with NEMEA shielding

5.2 Release/Deploy Operation:

Each DSA array was characterized in tests for release/deploy operation, those test yielded the following values:

Operation	Volts	Amp.	Watts	Secs.	Joules
	1.6	5.0	8.0	19.0	152.0
Release	1.2	4.0	4.8	40.0	192.0
EXA MDR/R1C 80 grams max.	1.5	3.5	5.3	67.0	351.8
	1.0	2.6	2.6	240.0	624.0
	2.1	3.0	6.3	8.0	50.4
Deploy	1.8	2.8	5.0	12.0	59.4
EXA MDH/R2 50 grams max.	1.9	2.6	4.8	20.0	96.9
	1.6	2.3	3.6	28.0	100.8

Table-5.1: Tests results of the Release/Deploy operations for IRVINE01

As seen in the test results, the best operation mode for release is the one using only 152 joules and for deploy, the one using 50.4 joules. The IRVINE01 satellite has 2 DSA arrays for a total nominal power of 7.5 W of power generation. Actual power is a little more if we take into account that the test were made on ground, at equatorial latitude not in LEO and yet it yielded a maximum output of 4.2 W per array.

The DSA arrays passed the Thermal Bake out test (10E-7 mbar @ 50C for 24 hours) and full vibration test for Dnepr and Long March 2D vibration profiles.

Test	QT	AT
Functional	✓	✓
Vibration	-	✓
Thermal Cycling	-	✓
Thermal Vacuum	-	✓
Cell Crack test	✓	✓
Continuity	✓	✓
Power Generation Performance	✓	✓
Flasher Test	✓	✓
Actuator Performance	✓	✓

Both DSA arrays, along with the full order of products for IRVINE01 were delivered on May 14[16] on Irvine, California, U.S.. Right now our DSA Deployable Solar Arrays are available through the CubeSatShop[20] website and as the time of writing this paper, 2 more arrays are ready for delivery for the upcoming IRVINE02 satellite, this new arrays include improvements in both in mass and performance that we will describe in an upcoming paper to be presented in the IAC2017 in Adelaide, Australia.

Table-5.2: Tests performed on the shipping units for IRVINE01

At this point 3 manifold configurations have been tested: A 1 panel (on ground), 2 panels (IRVINE01 and IRVINE02 on ground) and 3 panels (NEE-01 and NEE-02 in orbit), even the 3 panel configuration can be folded under the 6.5 mm cubesat standard clearance limitation and the interface is configurable to a variety of connectors to match the user preference or needs.

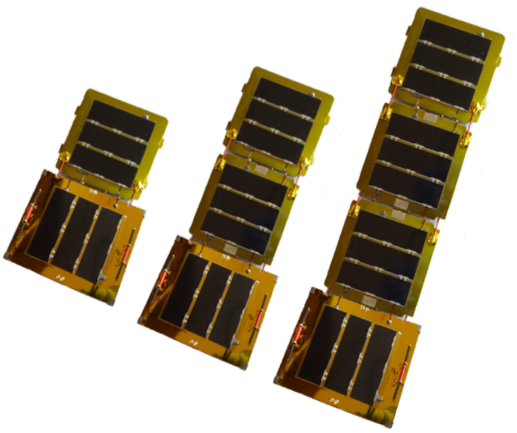

Fig-5.1 DSA arrays showing different panel and power configurations.

6. CONCLUSIONS:

The use of deployable solar arrays for 1U cubesats represents an advance not only in cubesat technology but also in affordability due the use of low cost solar cells; many 1U missions that were previously limited in power generation capability are now free of that constraint. Also the costs are affordable for this types of missions that otherwise will be forced to use bigger cubesat form factors increasing launch, engineering and testing costs.

The use of artificial muscles represents a breakthrough over the well-known thermal-knife technique which poses many problems during testing and risks in orbit, as it is a one-shot operation, if it fails, mission is over, but with artificial muscles that risk is eliminated as even the circuitry fails to provide the electrical power to heat the actuators, the heat of the sun will eventually deploy them after a few orbits as we observed with the NEE-01 PEGASUS and in many tests in the lab and in the thermal vacuum chamber.

Also, the use of deployable solar panels in a 1U cubesat enhances the cross section of the spacecraft helping it to comply with de-orbit best practices as supported by UN-OOSA proposals.

7. References:

1- *"ECSP: The Ecuadorian Civilian Space Program"* - EXA, Aerospace Operations Division - 2007- http://exa.ec.
2- Jaffer, Klesh, Nader, Koudelka "*Using a Virtual Ground Station as a Tool for Supporting Higher Education*"
3- '*Science and Technology in Ecuador'* - Books LLC, August 2010, USA
4- '*Earth Stations: HERMES-A/MINOTAUR'* - Books LLC, June 2010, USA
5- The first Ecuadorian Satellite official website http://pegaso.exa.ec
6- The official EXA website: http://exa.ec
7- EXA - BP-37: Guayaquil, Ecuador, April 4/2011
8- "*NEE-01 great video and sound*" - Mike Rupprecht blog, http://www.dk3wn.info/p/?p=33760
9- "*Project HERMES*" - Mike Rupprecht blog, http://www.dk3wn.info/p/?p=33136
10- "*DK3WN Satblog*" - Mike Rupprecht blog, http://www.dk3wn.info/p/?cat=111

11- Nader, Carrion, Falconi , "*Project Hermes*" – UN-OOSA/Austria/ESA Symposium on Small Satellite Programmes for Sustainable Development - Austrian Academy of Sciences, Graz, Austria
12- Nader, Carrion, Uriguen , "*ARGOS: HYPER AMPLIFICATION MANIFOLD FOR ENHANCING GROUND STATION RECEPTION*" 62nd IAC 2011 - SPACE COMMUNICATIONS AND NAVIGATION SYMPOSIUM
13- Nader , "*SPACE ENVIRONMENT ATTENUATION MANIFOLD SHIELD*" - 62nd IAC 2011 - 15th SYMPOSIUM ON SMALL SATELLITE MISSIONS (B4) - Generic Technologies for Nano Platforms (6B),
14- EXA selected to provide space hardware to the USA http://exa.ec/bp65/index-en.html
15- ISISpace Launch 03 Campaign
16- EXA completes its first export of space hardware to the U.S. http://exa.ec/bp66/index-en.html
17- "*Ecuador already has its 2nd satellite in space*" http://www.andes.info.ec/en/news/ecuador-already-has-its-second-satellite-space-nee-02-krysaor.html
18- NEE-01 PEGASUS tracking online: http://www.n2yo.com/satellite/?s=39151
19- NASA NSSDC: NEE-01 PEGASUS: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2013-018B
20- http://www.cubesatshop.com/product/solar-panels/
21- WIRED: "*Ecuador launches its first satellite, has webcam, will search for asteroids*" http://www.wired.co.uk/news/archive/2013-04/26/first-ecuador-satellite
22- "*Ultra thin, deployable, multipanel solar arrays for 1U cubesats*" https://www.academia.edu/772242/Ultra_thin_deployable_multipanel_solar_arrays_for_1U_cubesats
23- Nader, Carrion, Uriguen, Drouet, Allu, "*NEE-01 PEGASUS: THE FIRST ECUADORIAN SATELLITE*"- 62nd IAC 2011, 15th SYMPOSIUM ON SMALL SATELLITE MISSIONS (B4) - 12th UN/IAA Workshop on Small Satellite Programmes at the Service of Developing Countries (1) –https://www.academia.edu/772243/NEE-01_PEGASUS_The_first_Ecuadorian_Satellite
24- Nader, "*CYCLOPS: REAL TIME VIDEO TRANSMISSION FROM ORBIT ON A 1U CUBESAT MISSION*", https://www.academia.edu/772240/CYCLOPS_REAL_TIME_VIDEO_TRANSMISSION_FROM_ORBIT_ON_A_1U_CUBESAT_MISSION
25- Nader, Carrion, Uriguen - "*SESCA: SPACE ENVIRONMENT SIMULATION CHAMBER FOR ACCURATE GROUND TESTING OF NANO SATELLITES*", https://www.academia.edu/772222/SESCA_SPACE_ENVIRONMENT_SIMULATION_CHAMBER_FOR_ACCURATE_GROUND_TESTING_OF_NANO_SATELLITES
26- Nader, Kelso - "The PEGASUS incident: The loss of the first Ecuadorian satellite and its recovery.", https://www.academia.edu/8614951/THE_PEGASUS_INCIDENT_THE_LOSS_OF_THE_FIRST_ECUADORIAN_SATELLITE_AND_ITS_RECOVERY
27- PHYS.ORG: "*Ecuador warns satellite could hit rocket remains (Update)*", May 22, 2013, http://phys.org/news/2013-05-ecuador-satellite-rocket.html
28- BBC: "*Ecuador Pegasus satellite fears over space debris crash*", 24 May 2013, http://www.bbc.com/news/world-latin-america-22635671
29- "*JE9PEL Wisp page: NEE-01 PEGASO*" http://www.ne.jp/asahi/hamradio/je9pel/nee_pega.htm
30- "*Russian Dnepr conducts record breaking 32 satellite haul*" , November 21, 2013 by William Graham - http://www.nasaspaceflight.com/2013/11/russian-dnepr-record-breaking-32-satellite-haul/
31- WIRED: "*Ecuador's first satellite collides with Soviet rocket debris, possibly survives*", http://www.wired.co.uk/news/archive/2013-05/24/ecuador-satellite-crash
32- UNIVERSE TODAY: "*A tale of two satellites*" http://www.universetoday.com/103650/space-debris-a-tale-of-two-satellites/
33- NASA Orbital Debris Quarterly News – "*High-Speed Particle Impacts Suspected in Two Spacecraft Anomalies*" - http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv17i3.pdf
34- SATNEWS: "*Ecuadorian Civil Space Company (EXA)—Imagery Involvement + An Important Recovery*" - http://www.satnews.com/story.php?number=1323163133
35- El TELEGRAFO: "*Señal de Pegaso fue recuperada gracias a Krysaor*" - http://www.telegrafo.com.ec/politica/item/senal-de-pegaso-fue-recuperada-gracias-a-krysaor.html
36- ANDES: "*El satélite ecuatoriano Krysaor emitió su primer video y recuperó contacto con su gemelo Pegaso*"
37- PHYS.ORG: "*Ecuadoran satellite starts transmitting*" - http://phys.org/news/2014-01-ecuadoran-satellite-transmitting.html
38- ELCOMERCIO: "*EXA recuperó a Pegaso y su gemelo ya transmite video*" - http://www.elcomercio.com/tendencias/ciencia/exa-recupero-a-pegaso-y.html
39- GIS-METEO.RU: "*Эквадор нашел свой потерянный спутник*"
40- SPACEDIGEST: *"FIRST ECUADORIAN SATELLITE PEGASO IS IN CONTACT AGAIN!*" - http://spacedigest.net/en/280114_pegaso/
41- Rajagopalan, Porras, Nader and others. "*Awaiting Launch: Perspectives on the draft ICOC for outer space activities*"
42- Nader, Uriguen, Carrion. "*THE ECUADORIAN EXPERIENCE IN SPACE*" , 65th IAC 2014 – 21st IAA SYMPOSIUM ON SMALL SATELLITE MISSIONS (B4) 15th UN/IAA Workshop on Small Satellite Programmes at the Service of Developing Countries
43- "*Realities of space debris: the Pegasus satellite*", Nader, Carrion - "*Space Equities: The Role of the Americas in Building Norms of Behavior*", UNIDIR regional seminar, Mexico city – 2013
44- Nader , Drouet, Nader, HIGH ENERGY DENSITY BATTERY ARRAY FOR CUBESAT MISSIONS - 67th International Astronautical Congress 2016, 23rd IAA SYMPOSIUM ON SMALL SATELLITE MISSIONS (B4), Generic Technologies for Nano/Pico Platforms (6B),