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The first CREDO registration of extensive air shower

Michał Karbowiak[1], Tadeusz Wibig[1], David Alvarez-Castillo[2,5], Dmitriy Beznosko[3], Alan R Duffy[4], Dariusz Góra[5], Piotr Homola[5], Marcin Kasztelan[6] and Michał Niedźwiecki[7]

[1] University of Lodz, Faculty of Physics and Applied Informatics, 90-236 Łódź, Pomorska 149/153, Poland
[2] Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Joliot-Curie str. 6, 141980 Dubna, Russia
[3] Clayton University, 2000 Clayton State Blvd, Morrow, GA 30260, United States of America
[4] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[5] The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Kraków, Radzikowskiego 152, Poland
[6] National Centre for Nuclear Research, Astrophysics Division, 90-558 Łódź, 28 Pułku Strzelców Kaniowskich 69, Poland
[7] Faculty of Computer Science and Telecommunications, Cracow University of Technology, Warszawska 24st 31-155 Cracow, Poland

E-mail: t.wibig@gmail.com

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Abstract

The Cosmic-Ray Extremely Distributed Observatory (CREDO) is the project to search and study ultra high-energy cosmic ray particles from deep space producing simultaneous extensive air showers over the entire exposed surface of the Earth. The concept of the CREDO infrastructure assumes absorbing all kinds of cosmic ray data from any apparatus all over the world, including professional instruments, educational detectors and arrays, and popular devices such as smartphones. We discuss here the usefulness and possibilities of using the last one and present the educational CREDO-Maze mini array comprised of four CosmicWatch detectors. This simple and affordable apparatus is shown to be able to register the extensive air showers and can be used to study cosmic rays much more effectively than the simple two-detector CosmicWatch muon telescope station. The further development direction is indicated.

Keywords: cosmic rays, extensive air showers, particle detectors, cosmic ray ensambles

1. Introduction

1.1. Installation

Everyone can use the constant and uniform bombardment of the Earth surface by cosmic rays to study properties of high energy particles (especially muons), test relativity (e.g. the twins paradox), monitor the impacts of space weather and more. Such studies are important additional activities for children in a range of school lessons as well as after-hours activities. There are many such activities regularly undertaken and described in the literature, to name but a few:

- *An Educational Study of the Barometric Effect of Cosmic Rays with a Geiger Counter* by Famoso, La Rocca and Riggi (2005) [1],
- *Educational Cosmic Ray Experiments with Geiger Counters* by Blanco *et al* (2006) [2],
- *Geiger Counters Offer Powerful Way to Teach Detection Methods* by Blanco *et al* (2006) [3],
- *Educational Studies of Cosmic Rays with Telescope of Geiger–Muller Counters* by Wibig *et al* (2006) [4],
- *Cosmic Ray Measurements by Scintillators with Metal Resistor Semiconductor Avalanche Photo Diodes* by Blanco *et al* (2008) [5],
- *Cosmic Rays with Portable Geiger Counters: From Sea Level to Airplane Cruise Altitudes* by Blanco, La Rocca and Riggi (2009) [6],
- *An Inexpensive Cosmic Ray Detector for the Classroom* by Goldader and Choi (2010) [7],
- *The EEE Project: Cosmic Rays, Multigap Resistive Plate Chambers and High School Students* by Abbrescia *et al* (2012) [8],
- *High Energy Astroparticle Physics for High School Students* by Krause *et al* (2015) [9],
- *μCosmics: A Low-Cost Educational Cosmic Ray Telescope* by Tsirigotis and Leisos (2019) [10].

1.2. Usage

These are related to working with single cosmic ray muons which are quite abundant (i.e. high counting rate with the single detector) and highly penetrating (they are not stopped significantly by the concrete floors). However the most interesting and attractive would be studying the phenomenon of extensive air shower (EAS), a cascade of elementary particles, mostly photons and electrons, but also some muons or even high energy hadrons traveling almost at the speed of light from the upper atmosphere to the surface of the Earth. They arrive as a disk of millions of particles for one short instance. The source of very high energy particles that initiated such showers is, in general, not known as well as the mechanism of their acceleration from astrophysical sources. The mystery of (high energy) cosmic rays has stood for almost a century and observing and studying these EAS can be exciting and stimulating for the young minds.

The concept of a network of detectors, suitable for studies of EAS, was introduced in some locations at the end of previous millennium - the best known example is the High School Project on Astrophysics Research with Cosmics (HiSPARC) [11] in the Netherlands; as well as WALTA [12], NALTA, ALTA [13], SALTA, CZELTA [14], SKALTA, CHICOS [15], CROP. Some of them are ephemeral, some are in a different phase of realization.

The Cosmic Ray Extremely Distributed Observatory (CREDO) Project officially started operations on September 11th 2019, but the idea is nearly three years old. By design it was a large international enterprise, currently consisting of 13 countries involving many scientific and educational institutions. It was presented and discussed in many international conferences, e.g. [16–19].

The main scientific purpose of CREDO is to detect the so-called cosmic ray ensembles [20]. They are the bunches of very high energy cosmic rays producing simultaneous Extensive Air Showers over the entire exposed surface of the Earth. Such a phenomenon has never been seen, but there are several models under which such an event is a possibility. The concept of the CREDO infrastructure assumes absorbing all kinds of cosmic ray data from any apparatus all over the world, including professional instruments, educational detectors and arrays, and popular devices such as smartphones. While it is expected that the cosmic ray experiments will be joining common studies via the CREDO database, an additional, original engineering effort is required to complement the (potentially) available infrastructure, so that activities dedicated to the main scientific objective of the CREDO Collaboration—the search for cosmic ray ensembles—can be carried out independently of potential delays caused by external circumstances. This effort has begun with constructing our own, very simple EAS array, called CREDO-Maze and demonstrating that it registers air showers. In this paper, we describe this milestone achievement.

The concept of the CREDO-Maze array was developed based on the 20 years old Roland Maze Project [21, 22]. The technology today has developed greatly and the local shower array idea of Linsley [23] can now be implemented much more easily and, critically, much more cheaply. Eventually we wish to present high-schools with sets of at least four 'professional' cosmic ray detectors connected locally and forming the small school EAS array. These will use plastic scintillators instead of smartphone cameras, bespoke fast electronics instead of the smartphone application, and a more convenient connection to the wider CREDO database. But this is not all. We have established some physical arrangements that can be used by physics teachers in the standard physics education course showing properties of elementary particles, radiation attenuation, effect of interaction of particles with matter, etc. There are many historical experiments (dating back to the 40 s) that can be repeated in the classroom or during afterhours activities.

The final design of the small local EAS array is still in development, but to test the working principle we have used small detector available on the market: the CosmicWatch Desktop Muon Detector [24]. One set of CosmicWatch contains two small (5 cm $\times$ 5 cm) scintillators monitored by silicon photomultipliers (SiPM) and slow electronics based on an Arduino microcontroller, that allows students to connect them to the computer and analyse simultaneous registration of signals from both detector laying one above the other, which flags muon passing through both scintillators.

We have used two CosmicWatch sets, that is four individual scintillation detectors. We bypassed the CosmicWatch electronics and used the raw SiPM signal. We combine four available individual detector signals into six pairs of fast coincidence units. The coincidence window width of 200 ns was used. This short time ensured that the signal rate from uncorrelated muon (and other noise sources) was of order of tens per minute to ensure that non-EAS signals will not disrupt our shower registrations. The logic of our array is such that if any coincidences appear in any of six outputs, the data is immediately stored in a fast register and the trigger starts the slower electronics (based on an Arduino microcontroller). This last stage reads the register and transfers all six bits to the computer where they are stored together with the actual time stamp in a file for further analysis. It is shown in figure 1.

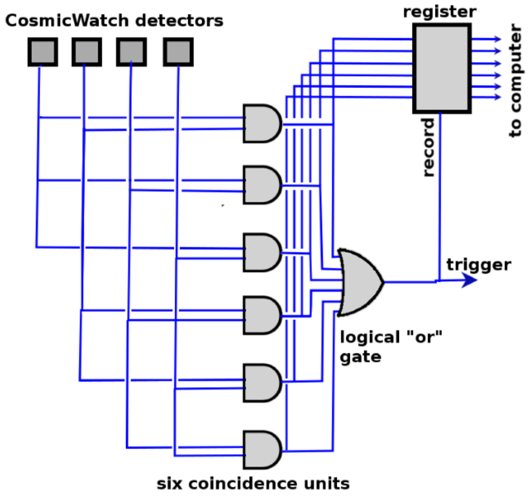

Figure 1. Logical scheme of our four detectors of the CREDO-Maze EAS array.

2. Measurement

Before we start using the array to search for an EAS, we first tested it to be sure that the registered events were real.

The first test was to place four detectors in one tower arrangement. The CosmicWatch detectors are expected to give a signal for single muons. The threshold was set for all detectors individual signal forming amplifier/comparators on the same level of about 30 mV. Importantly, the four detector rates were not exactly the same, though we will consider this fact later.

The single muon passing at least two detectors can trigger the first and the second detectors, looking from the top of the tower and nothing

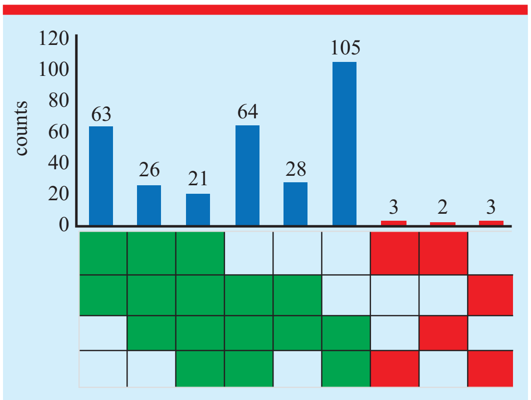

Figure 2. Test of the CREDO-Maze array. Four CosmicWatch detectors stacked on top of each other and the number of recorded events corresponding to the configuration of the hit counters shown at the bottom of the figure.

more, leaving the tower from the side: (1, 2), can travers (1,2,3), (1,2,3,4), but also (2,3), (2,3,4) and (3,4). Other possibilities for the ideal geometry are forbidden. Figure 2 shows results of the short run with the tower geometry.

The extremely low count for forbidden coincidence (with the gap between the fired detectors) configurations give us confidence that in the majority of cases CosmicWatch detector in our array respond correctly to the passage of the single relativistic charged particle.

The asymmetry between the first (1,2) and sixth (3,4) configurations, and (1,2,3) and (2,3,4) is due to the fact that the detector thresholds are not set perfectly. The number of counts shown in figure 2 suggests that the detector number 1 seems to have the threshold set a little too high. However, this imperfection does not affect the general reasonable behavior of the whole array. After the test, we arrange four detectors in the plain with irregular (not rectilinear) configuration of the step of order of 1 meter. Different geometries were tested without significant differences.

The final geometry is shown in figure 3. We place our CREDO-Maze mini array on a windowsill.

3. Simulations

Simulations, especially for cosmic ray and EAS studies are the common and obvious tooll for drawing conclusions from factsobserved in the sometimes very complex experiments. For many years, huge Monte Carlo programs have been written trying to recreate the development of atmospheric cascades from the sometimes only partially known simple physical relationships.

There are several such programs nowadays. They are available to all interested scientists and experimental groups and they are widely used in the study of large bundles. On the one hand, it unifies the mechanisms of discussing of measured results, but on the other hand, it can lead to misunderstandings if these programmes are used beyond their range of application. In shower simulation programs it is most often about the energy range of incomming particles. The dangers often lie in exceeding the upper energy range and using models of high energy interactions extrapolated beyond the recommended and reasonable, tested limit. The lower range of applicability of models seems to be safe. The low energy models are well tested, but it must be remembered that they are necessarily bespoke for applications in simulation of huge EAS simulation programs, after all, they have to work effectively in the area, where mostly their average characteristics are important.

It seems obvious that one of the available packages such as CORSIKA [25] can be used to test the proposed experiment. It was developed at Forschungszentrum Karlsruhe already in the previous century and it is probably the best known and widely used tool in cosmic ray experimental studies. Many additional options makes it vary flexible and convenient application in almost all issues related to shower physics. However, there seem to be exceptions to this. One of them is the simulation of very small showers (with the limit of single muons recorded, for example, by smartphones in the CREDO Project, or typically

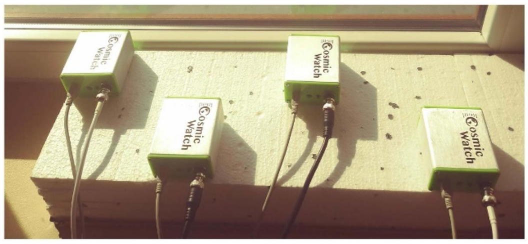

Figure 3. View of the CREDO-Maze array.

by CosmicWatch counters). This is a transition through the lower limit of the energy of cosmic ray particles. Due to the steep spectrum reaching down to 1GeV and even less, the particles observed on the earth's surface are remnants of interactions that took place kilometers above and whom, thanks to a lucky coincidence, managed to reach a depth of 1000g cm^{-2} in the atmosphere. Observations of such particles are very far from 'average' expectations. They are in fact very rare cases, fluctuations,whose description in large EAS simulation programs is almost irrelevant. Besides, using huge simulation programs in such cases, where other options are possible (which we will talk about in the moment) is like shooting a sparrow with a cannon.

The particles which could produce coincidence in our mini array have to come in one instant (within 200 ns) at the surface of about $1\mathrm{m}^2$. Considering the small effective area of CosmicWatch detectors, the particle density of particles in such event has to be rather high, or if it is actually low, the frequency of such low-density events (extremely small 'extensive air showers') should be very high. Local particle densities relates certainly to shower physics, but it is very low energy physics. According to the CORSIKA program, on average showers initiated by the proton of 1 TeV (1000GeV!) energy gives about 30 charged particles at a moment of which about 2/3 are muons . They're all spread out over a thousand square meters. Using the CORSIKA for energies 10 times bigger (the particle cosmic ray flux above will be 100 times smaller respectively) the showers will consist 350–450 charged particles (of which 1/3 are muons) distributed around the center of the showers with the densities lower than ~ 0.1 per m^2 everywhere (on the ground level). The uncertainty of this numbers are related with the particular interaction model used in the CORSIKA simulations. It is quite problematic and doubtful to reconcile the measurement of a single muon flux (or low particle density spectrum) with the CORSIKA program simulation results. The number of models and their parameters that can affect the results is quite large.

The way out of the impasse is to compare the results of the measurements with other kind of simulation program based on the known for many years shower particle density spectrum.

A measurement consisting of registering many particles in an apparatus with a specific collection area at a single moment leads to a determination of the frequency of occurrence of specific particle densities - the density spectrum. The problem of determining shower particle density spectrum was studied almost immediately after extensive air showers were discovered. We used the result obtained by Broadbent *et al* [26]. The form of the shower density integral spectrum used is

$$N(x) = 620 \times x^{-1.425}, \tag{1}$$

where x is the particle density (per m^2) and N is the number of events of densities higher than x per hour per m^2. This equation is valid for the densities from 5 to 500 particles per m^2, which is within our expectations of the density range triggering the CREDO-Maze mini array.

There are many other spectra which can be used in the literature, for example [26], quite close to the Broadbent spectrum, the result of Norman *et al*:

$$N(x) = 540 \times x^{-1.39}. \tag{2}$$

Greisen gives the similar expression for the density spectrum in the range $1 < x < 10^4\ \mathrm{m}^{-2}$ with the index of -1.3 [27]

Abrupt change of the density spectrum slope was for the first time observed by Zawadzki in 1957 [28]. Ashton and Parvaresh published such a broken power law spectrum [29], which differs by the factor of 2 from both equations (1) and (2):

$$N(x) = \begin{cases} 411 \times x^{-1.5} & \text{for} \quad 40 < x < 1000\ \mathrm{m}^{-2} \\ 13000 \times x^{-2} & \text{for} \quad 1000 < x < 5000\ \mathrm{m}^{-2} \end{cases}. \tag{3}$$

The results of our simulation should hence be treated with caution [30].

In our simulation program we generated millions of test densities according to equation (1) and then for each one we calculated if every single detector was triggered or not. The Poisson distribution with the average equal to the generated density was certainly applied. In order to examine the sensitivity of the experiment to the assumed

Table 1. Average rate of events (per hour) with different number of simultaneously hit CosmicWatch detectors in the CREDO-Maze mini array.

	rate
one detector is hit	6.5 (~ one per 10 minutes)
two-fold coincidence	0.7 (~ once per hour)
three-fold coincidence	1/7 (~ three per day)
four-fold coincidence	1/40 (~ once per two day)

Table 2. Ratios of 3-fold and 4-fold to 2-fold coincidences rate according to our simulations for different values of cosmic ray spectrum index.

index	$\frac{\text{three}-\text{fold}}{\text{two}-\text{fold}}$	$\frac{\text{four}-\text{fold}}{\text{two}-\text{fold}}$
−1.8	0.132	0.039
−1.6	0.174	0.067
−1.4	0.228	0.113
−1.2	0.295	0.187

slope of the density spectrum, we have calculated the rate for several values of the spectrum index. Results of the simulations are shown in table 1.

Single hits are obviously lost in the background of single muon counts, so only three independent quantities remain. One uncertain parameter here is the normalization, so the ratios of three-fold coincidences to two-fold coincidences rates and four-fold coincidences to two-fold coincidences rates are to be used. These observables are independent from the overall normalization (actual solid angle, shielding, etc), and they depend mostly on the density spectrum index. Our simulations for different index values are shown below in table 2. The effect is clearly seen.

Our mini-array test run lasted for little more than a week, and during this time we registered: 94 two-fold coincidences, two three-fold and one all four hits event. The time series of our measurement is shown in figure 4.

The number of more than 2-fold coincidences is much too low, even if we take into account absolutely insignificant statistics. To perform the accurate measurement we need to have detectors which response in the same way to particle traversing the scintillator, which is not exactly this case (see figure 2) and locate them in a more convenient geometry and place. But anyway, the comparison of the simulation result with our measurement give us the confidence, that our CREDO-Maze mini array registered real EAS.

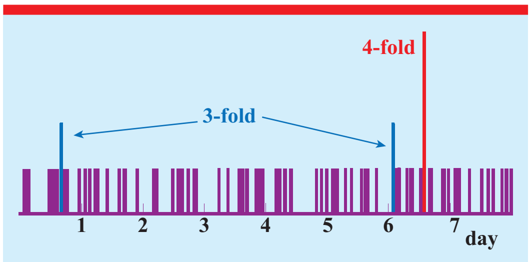

Figure 4. Time serial of the coincidences recorded in CREDO-Maze mini-array. Short bars (black) shows 2-fold coincidences, longer (blue) ones: 3-fold, and the one longest (red) bar is the only one 4-fold coincidence registered during the ~ week long run.

4. Future development

In the next prototype of the CREDO-Maze array the size of scintillators should be increased to at least 10 cm × 10 cm and we would like to collect the scintillation light with small SiPMs, of about 1 mm size, and to use wavelength shifting fibers as light guides.

With the bigger scintillator the statistics will be gathered much faster by each array, but also the arrays of the standardized detectors in the possession of many schools will allow students to combine their results multiplying the statistics and to achieve an accuracy for successful analysis of the spectrum index.

The four bigger detectors allow students to measure the so-called decoherence curve. Thus, to reconstruct the famous Auger and Maze experiment on the roof of École Normale Supérieure, where the EAS were discovered.

With the four detectors, a few of Rossi's experiments can be also recreated: the Rossi transition curve, attenuation of muons, and, with the slightly modified coincidence circuit, there is even the possibility to study muon decay.

5. Summary

We have shown that the CREDO-Maze mini array using CosmicWatch detectors registered the first EAS. It demonstrates the feasibility and economic availability of a global air shower detection system oriented on observing cosmic ray ensembles; large scale cosmic ray correlations, as planned in CREDO. Achieving the ability to observe such phenomena will be synonymous with opening up a new information channel to the Universe, of importance for multi-messenger astroparticle physics, including the potential of far-going impact in astrophysics, high energy particle physics, cosmology, and even foundations of science.

ORCID iDs

Michał Karbowiak https://orcid.org/0000-0002-2415-5643
Tadeusz Wibig https://orcid.org/0000-0002-2078-0580
David Alvarez-Castillo https://orcid.org/0000-0003-1874-8116
Alan R Duffy https://orcid.org/0000-0002-9636-1809
Dariusz Góra https://orcid.org/0000-0002-4853-5974
Piotr Homola https://orcid.org/0000-0002-1956-9948
Marcin Kasztelan https://orcid.org/0000-0002-7718-2725
Michał Niedźwiecki https://orcid.org/0000-0003-2830-9133

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References

[1] Famoso B *et al* 2005 *Phys. Educ.* **40** 461
[2] Blanco F *et al* 2006 *Il Nuovo Cimento C* **29** 381
[3] Blanco F *et al* 2006 *Phys. Educ.* **41** 204
[4] Wibig T, Koł odziejczak K, Pierzyński R and Sobczak R 2006 *Phys. Educ.* **41** 542
[5] Blanco F *et al* 2008 *Phys. Educ.* **43** 536
[6] Blanco F *et al* 2009 *Eur. J. Phys.* **30** 685
[7] Goldader J D and Choi S 2010 *Phys. Teacher* **48** 594
[8] Abbrescia M *et al* 2012 *J. Instrumentation* **7** T11011
[9] Krause M *et al* 2015 High energy astroparticle physics for high school students arXiv:1508.03968
[10] Tsirigotis A G and Leisos A 2019 *Universe* **5** 23
[11] van Dam K *et al* 2019 The HiSPARC experiment *Nucl. Instrum. Methods Phys. Res.* A **959** 163577
[12] Wilkes R J, Berns H, Burnett T H and Gran R 2004 *IEEE Trans. Nucl. Sci.* **51** 1385
[13] Brouwer W *et al* 2005 *Nucl. Instrum. Methods Phys. Res.* A **539** 595
[14] Smolek K, Nyklíček M and Kovačíková P 2007 *Conf. Proc.* **958** 197
[15] Brobeck E 2009 Measurement of ultra-high energy cosmic rays with CHICOS *Report* California Institute of Technology 10192008-143041
[16] Dhital N *et al* 2018 *PoS* **301** 2017
[17] Góra D *et al* 2018 *Universe* **4** 2218
[18] Góra D *et al* 2019 Cosmic ray extremely distributed observatory: status and perspectives of a global cosmic ray detection framework arXiv:1908.04139
[19] Homola P *et al* 2019 Public engagement as a scientific tool to implement multi-messenger strategies with the Cosmic-Ray Extremely Distributed Observatory arXiv:1908.09734
[20] Woźniak K W *et al* 2019 For the Credo Collaboration vol 208 *EPJ Web Conf.* p 15006
[21] Gawin J *et al* 2002 *Acta Physics Polonica* B **33** 349
[22] Feder J *et al* 2005 *Int. J. Modern Phys.* A **20** 6881
[23] Linsley J 1985 Mini and super mini arrays for the study of highest energy cosmic rays *19th Int. Cosmic Conf., La Jolla, US OG9* pp 4–9
[24] Axani S N, Frankiewicz K and Conrad J M 2018 *J. Instrum.* **13** P03019
[25] Heck D and Knapp J, Capdevielle J N, Schatz G and Thouw T 1998 CORSIKA: a Monte Carlo code to simulate extensive air showers *Report* FZKA-6019
[26] Norman R J 1956 *Proc. Phys. Soc.* A **69** 804
[27] Greisen K 1960 *Annual Rev. Nuclear Science* **10** 63
[28] Zawadzki A, Wibig T and Gawin J 1998 *Nuovo Cim.* A **111** 329
[29] Ashton F and Parvaresh A 1975 *Int. Cosmic Conf.* **8** 2919
[30] Greider P K F 2010 Extensive air showers *High Energy Phenomena and Astrophysical Aspects* (Berlin: Springer)

Michał Karbowiak has been working as a physicist at the Faculty of Physics and Applied Informatics of the University of Lodz since 2014. He also works as a high school physics teacher. He is currently involved in experimental research of cosmic rays within the CREDO Project.

Tadeusz Wibig at present works as a professor at the Department of Theoretical Physics, University of Lodz. He has been engaged in the experimental and theoretical research on cosmic rays for over 40 years. He was a member of KASCADE, MAGIC and JEM-EUSO collaborations and currently he has been in CREDO for two years.