PROCEEDINGS OF SCIENCE

Integration and Calibration of the GAPS Antarctic Balloon Payload

Riccardo Munini[a,b,*] **and Field Rogers**[b] **for the GAPS collaboration**

[a] *INFN, Sezione di Trieste, I-34149 Trieste, Italy*

[b] *IFPU, I-34014 Trieste, Italy*

[c] *SSL UC Berkeley*

E-mail: riccardo.munini@ts.infn.it

With its inaugural Antarctic long-duration balloon mission in December 2024, the General Antiparticle Spectrometer (GAPS) will become the first experiment optimized to detect cosmic-ray antinuclei below 0.25 GeV/n. Detection of a single antideuteron in this energy range would be a smoking-gun signature of new physics, such as dark matter. The GAPS program will also provide a precision antiproton spectrum in a previously unprobed low-energy range, as well as leading sensitivity to antihelium-3. This new parameter space is accessible thanks to a novel particle identification method based on exotic atom formation, de-excitation, and annihilation. The method provides a unique signature for the negatively-charged antinuclei, facilitating excellent rejection of the positive-nucleus background, and does not require a magnet, enabling a large sensitive area for rare events. The GAPS instrument is designed to provide excellent discrimination power for rare events within the power and mass constraints of a long-duration balloon. The time-of-flight, composed of 160 scintillator paddles, provides the system trigger as well as the GAPS energy scale. The 2.5 m^3 tracker volume is instrumented with 10-cm-diameter silicon sensors, which serve as the target, X-ray spectrometer, and particle tracker. Together, a large-area radiator and an integrated oscillating heat pipe system cool the payload without a bulky cryostat. This contribution reports the integration and calibration of the GAPS science payload, including the performance of the sensitive detector subsystems, the cooling system, the power distribution, and data acquisition and onboard event processing.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)180

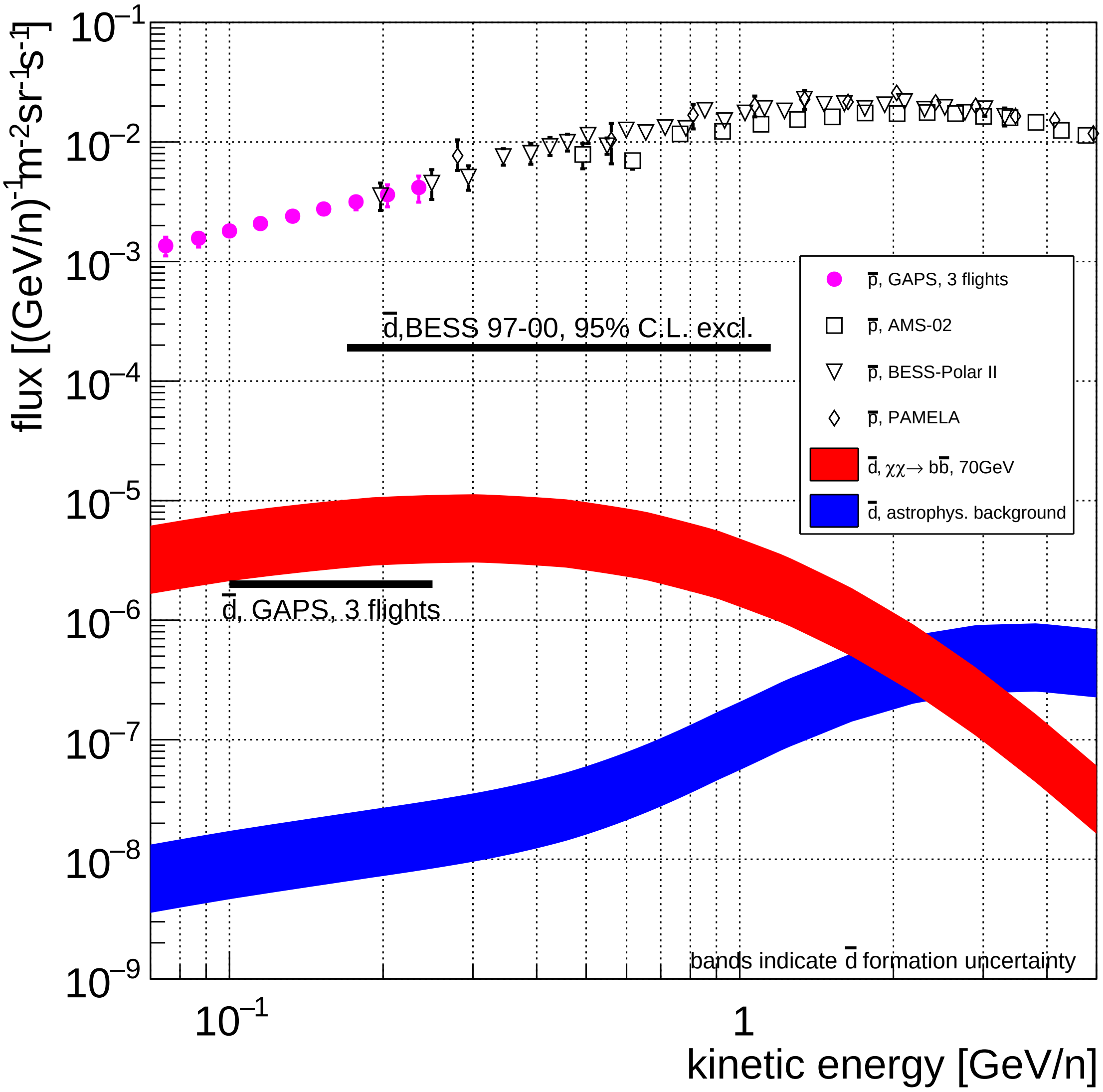

Figure 1: The expected sensitivity of the GAPS Experiment to cosmic-ray antideuterons is compared to the predicted flux from a sample DM model (red) and predicted background from known astrophysics astrophysical backgrounds (blue, green) as well as limits by the BESS Experiment. Meanwhile, the expected GAPS sensitivity to antiprotons (orange) will result in a precision spectrum extending to lower energies than past measurements.

1. The GAPS science

The General Antiparticle Spectrometer (GAPS) [1–6] is the first experiment optimized to measure low-energy cosmic-ray antideuterons. As illustrated in Figure 1, low-energy cosmic-ray antideuterons constitute a dark matter (DM) probe that is uniquely free of astrophysical background. While antideuterons are expected from a range of DM models, production via known astrophysical processes is kinematically suppressed, so detection of low-energy antideuterons would indicate new physics [7].

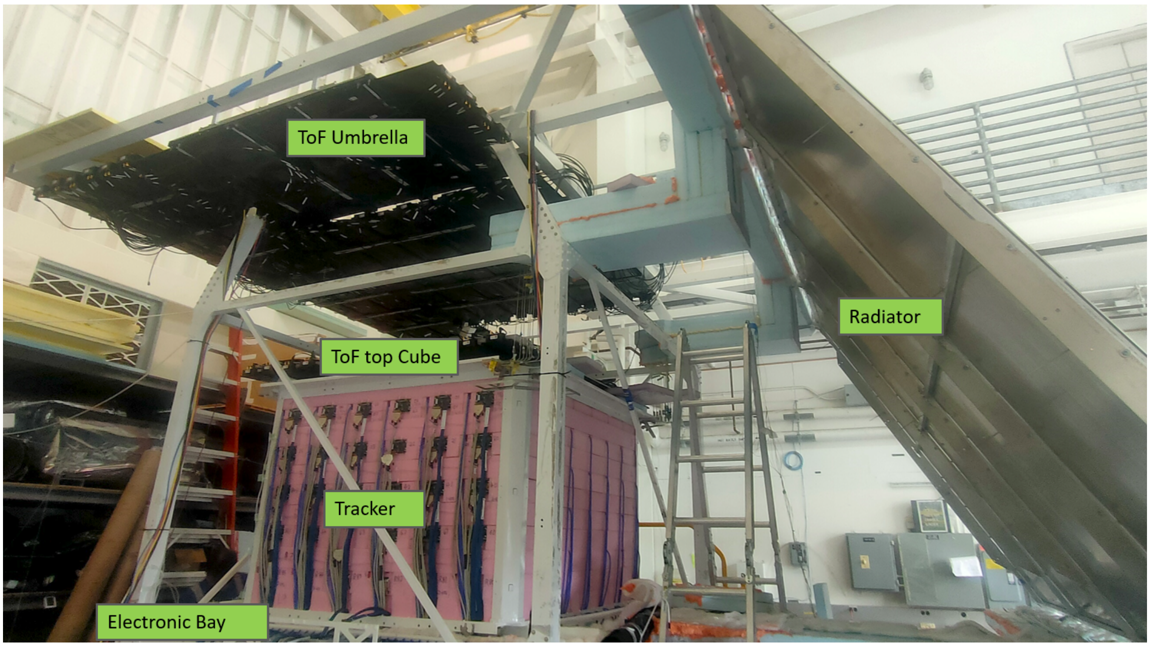

Figure 2: The GAPS experiment integrated at SSL. The 10-layer tracker is the core of the apparatus. The TOF appears partially integrated with the plastic scintillators forming the top Cube and the Umbrella. The radiatior of the passive cooling system is shown on the right.

The GAPS detector is designed for the kinetic energies below 0.25 GeV/n, where the signal-to-background is maximized for antideuterons from DM. GAPS will operate from an Antarctic long-duration balloon, which provides flights of about 35 days at 37 km altitude, and a latitude that minimizes geomagnetic effects. The first flight is expected for 2024. A novel exotic-atom-based detection technique provides identification power for antideuterons and a large sensitive area for rare events within the constraints of a balloon payload. Antinuclei are identified using a velocity measurement in combination with exotic atom signatures. GAPS is expected to produce a high-statistics measurement of the antiproton flux in the kinetic energy range of 0.08-0.25 GeV/n. It will also perform rare event searches resulting in leading sensitivity to low-energy antideuteron and antihelium-3 cosmic-ray fluxes. Figure 1 shows the expected antideuteron sensitivity assuming three flights of 30 days each.

2. The GAPS experiment

Figure 2 illustrates the integration of the GAPS science payload. The instrument consists of a TOF, which provides the velocity measurement and the trigger. It surrounds the tracker which serves as target and X-ray spectrometer. The TOF, composed of $160 \times 0.63 \times (108 - 180)$ cm^3 scintillator paddles, provides timing resolution < 400 ps using silicon-photomultiplier (SiPM) sensors and custom readout electronics. This subsystem consists of an inner Cube which encloses the tracker volume and an Umbrella panel positioned 90 cm above the Cube. In addition a Cortina surrounds the vertical sides of the Cube with a spacing of 30 cm. Figure 3 shows a close view of the Umbrella and top Cube Time of Flight integrated at Space Sciences Laboratory (SSL) in Berkeley as well as

Figure 3: The time of flight system composed by bars of plastic scintillators read out by SiPm.

a single plastic bar with the SiPm attached at its end. The 10-layer tracker is composed of 1440 8-strip, 10-cm diamter, 2.5 mm thick lithium drifted silicon (Si(Li)) sensors [8] instrumentng a 2.5m^3 volume. Seven planes are read out with custom application specific integrated circuits [9]. The other 3 planes provide additional target mass and thermal balance. . Each plane is composed by 6×6 modules, with one module consisting of four Si(Li) wafer each. Figure 3 shows the top layer of the tracker with a close view of one module with the four Si(Li) cylinders. The tracker is cooled in flight to -40°C using an oscillating heat-pipe (OHP) system [10] coupled to a radiator. In flight, the radiator points away from the sun, while during ground calibrations, it is coupled to a metal plate cooled by circulating -80°C methanol. The tracker is designed to provide <4 keV resolution for 20 - 100 keV X-rays as well as a dynamic range up to 100 MeV. This contribution discusses the integration of the GAPS tracker, TOF, thermal, power, and flight software subsystems. It additionally reports on the calibration of the detector subsystems and of the instrument as a whole.

3. The GAPS integration timeline

- Spring-Summer 2022: GAPS integration started at Bates Massachusetts Institute of Technology (MIT) laboratories with the mechanical structure assembling. Also the tracker integration started at MIT with a total of five planes integrated during this period.
- September 2022-February 2023: The instrument was moved to the SSL, University of California at Berkeley, where the remaining tracker planes were integrated. The tracker was

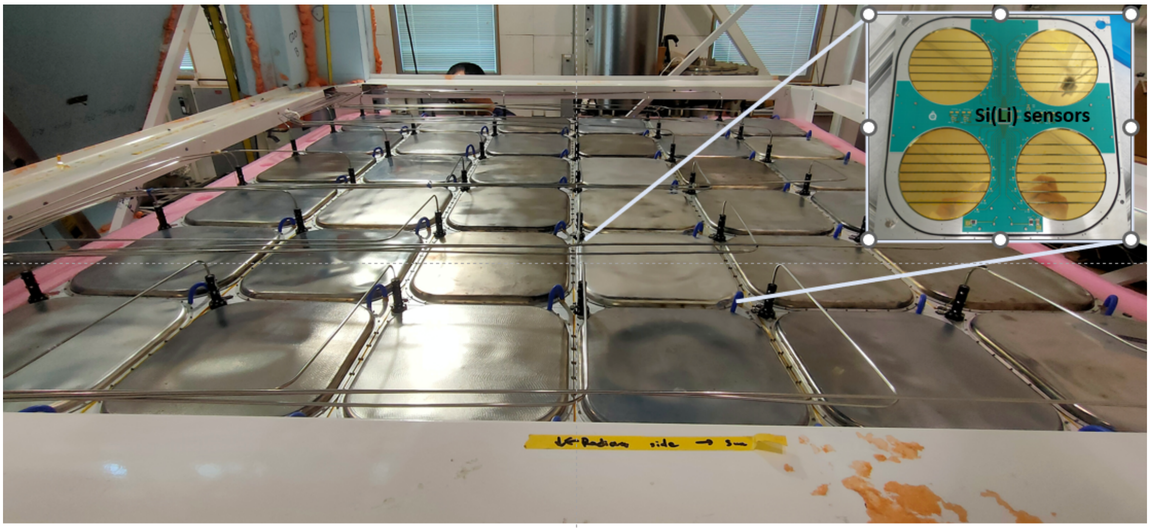

Figure 4: The top layer of the GAPS tracker. Each layer is composed by 6×6 modules made of 4 Si(Li) cylinder divided in 8 strips (see zoomed pictures on the top right). The tubes attached to each module compose the cooling system and ensure a nominal operating temperature between -40 and -45 degrees.

calibrated using cosmic muons, radioactive sources, and the self-calibration modes of the ASIC.

- Late 2022: the cooling system was fully integrated and tested. The thermal performance on the ground was monitored using thermocouples positioned throughout the tracker. The nominal performance was reached with the tracker modules all at approximately -30°C.
- April-May 2023: the top Cube and part of the Umbrella ToF are integrated and tested. The TOF timing response, energy scale, and velocity calculation are calibrated using cosmic muons. The tracker was also tested with muon acquisition using the ToF trigger. The system interfaces and integrated performance are also calibrated using cosmic muons.
- June 2023: GAPS was shipped to the National Technical System (NTS) facility in Los Angeles for thermal vacuum test (TVAC). The TVAC validated the comprehensive thermal model for the instrument. Both the overall instrument temperatures from the coldest to the hottest temperatures expected, as well as instrument subsystems, operated consistent with this model. The GAPS instrument had full functionality, and muons were recorded on all detector modules except of one, which can be repaired.
- July 2023: the instrument was moved to Columbia Nevis Laboratory.

4. Future integration time-line

- Fall 2023: the instrument will be reassembled at Columbia laboratories in Nevis, New York.
- Winter 2023 - Spring 2024: extensive muon data taking for tracker calibration and TOF system operation will be performed. Tracker Si(Li) will be calibrated with X-ray sources.

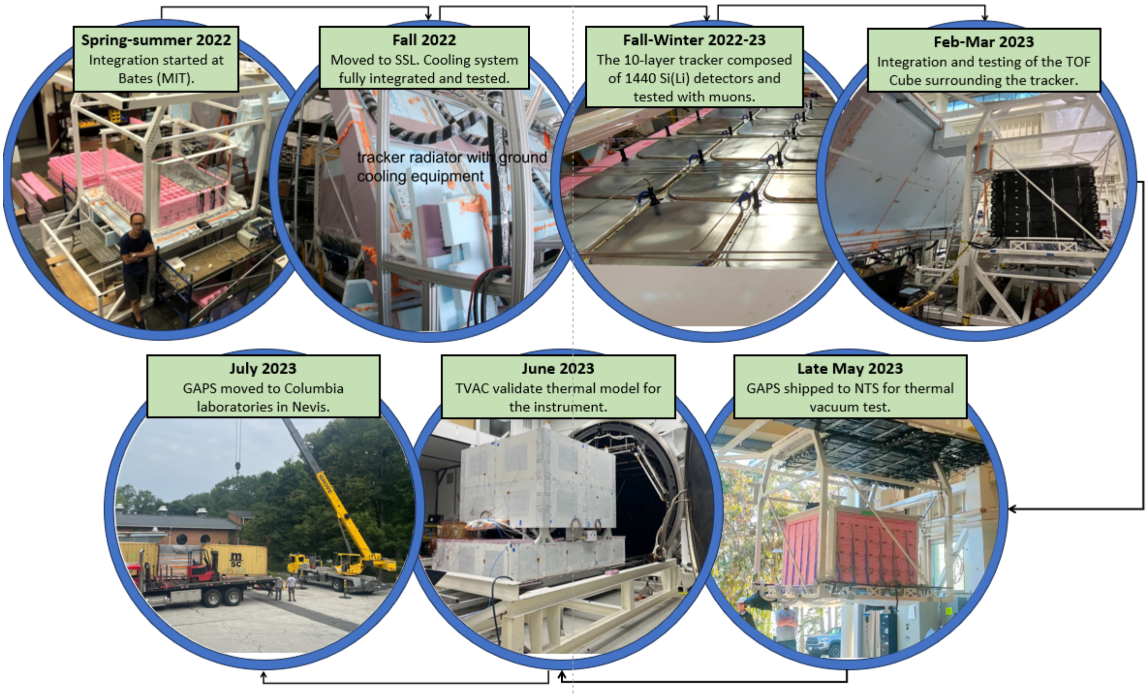

Figure 5: Timeline for the integration of the GAPS instrument to date.

- June 2024: the instrument will be moved to NASA facilities in Palestine, Texas for integration with the ballooncraft and compatibility and hang test.
- Fall 2024: the detector will be shipped to the McMurdo station where GAPS will be tested before the launch.
- December 2024: launch for the first 30 duration balloon flight.

References

[1] K. Mori et al., deexcitation of exotic atoms," ApJ vol. 566, 2002

[2] C.J. Hailey, New J Phys., vol. 11, 2009

[3] T. Aramaki et al., Astropart. Phys., vol. 74, 6–13, 2016

[4] T. Aramaki et al., Astropart. Phys., vol. 59, 12–17, 2014

[5] N. Saffold et al., Astropart. Phys., vol. 130, 102580, 2021

[6] F. Rogers et al., Astropart. Phys., vol. 145, 2023

[7] N. Fornengo et al., JCAP, vol. 2013, 2013.

[8] F. Rogers et al., JINST, vol. 14, 2019

[9] M. Manghisoni et al., In Proceedings of IEEE NSS/MIC, 2021

[10] H. Fuke et al., In Proceedings of IEEE NSS/MIC, 2019

Full Authors List: GAPS

T. Aramaki[1], M. Boezio[2,3], S. E. Boggs[4], V. Bonvicini[2], G. Bridges[5], D. Campana[6], W. W. Craig[7], P. von Doetinchem[8], E. Everson[9], L. Fabris[10], S. Feldman[9], H. Fuke[11], F. Gahbauer[5], C. Gerrity[8], L. Ghislotti[15,16], C. J. Hailey[5], T. Hayashi[5], A. Kawachi[12], M. Kozai[13], P. Lazzaroni[15,16], M. Law[5], A. Lenni[3], A. Lowell[7], M. Manghisoni[15,16], N. Marcelli[18], K. Mizukoshi[27], E. Mocchiutti[2,3], B. Mochizuki[7], S. A. I. Mognet[19], K. Munakata[20], R. Munini[2,3], S. Okazaki[27], J. Olson[22], R. A. Ong[9], G. Osteria[6], K. Perez[5], F. Perfetto[6], S. Quinn[9], V. Re[15,16], E. Riceputi[15,16], B. Roach[23], F. Rogers[7], J. L. Ryan[9], N. Saffold[5], V. Scotti[6,24], Y. Shimizu[25], K. Shutt[7], R. Sparvoli[17,18], A. Stoessl[8], A. Tiberio[26,29], E. Vannuccini[26], M. Xiao[23], M. Yamatani[11], K. Yee[23], T. Yoshida[11], G. Zampa[2], J. Zeng[1], and J. Zweerink[9]

[1]Northeastern University, 360 Huntington Avenue, Boston, MA 02115, USA [2]INFN, Sezione di Trieste, Padriciano 99, I-34149 Trieste, Italy [3]IFPU, Via Beirut 2, I-34014 Trieste, Italy [4]University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 90037, USA [5]Columbia University, 550 West 120th St., New York, NY 10027, USA [6]INFN, Sezione di Napoli, Strada Comunale Cinthia, I-80126 Naples, Italy [7]Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, CA 94720, USA [8]University of Hawai'i at Mānoa, 2505 Correa Road, Honolulu, Hawaii 96822, USA [9]University of California, Los Angeles, 475 Portola Plaza, Los Angeles, CA 90095, USA [10]Oak Ridge National Laboratory, 1 Bethel Valley Rd., Oak Ridge, TN 37831, USA [11]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara, Kanagawa 252-5210, Japan [12]Tokai University, Hiratsuka, Kanagawa 259-1292, Japan [13]Polar Environment Data Science Center,Joint Support-Center for Data Science Research,Research Organization of Information and Systems,(PEDSC, ROIS-DS), Tachikawa 190-0014, Japan [15]Università di Bergamo, Viale Marconi 5, I-24044 Dalmine (BG), Italy [16]INFN, Sezione di Pavia, Via Agostino Bassi 6, I-27100 Pavia, Italy [17]INFN, Sezione di Roma "Tor Vergata", Piazzale Aldo Moro 2, I-00133 Rome, Italy [18]Università di Roma "Tor Vergata", Via della Ricerca Scientifica, I-00133 Rome, Italy [19]Pennsylvania State University, 201 Old Main, University Park, PA 16802 USA [20]Shinshu University, Matsumoto, Nagano 390-8621, Japan [22]Heliospace Corporation, 2448 6th St., Berkeley, CA 94710, USA [23]Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA [24]Università di Napoli "Federico II", Corso Umberto I 40, I-80138 Naples, Italy [25]Kanagawa University, Yokohama, Kanagawa 221-8686, Japan [26]INFN, Sezione di Firenze, via Sansone 1, I-50019 Sesto Fiorentino, Florence, Italy [27]Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba 305-8505, Japan [28]Research and Development Directorate, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan [29] Universita' degli studi di Firenze, via Sansone 1, I-50019 Sesto Fiorentino, Florence, Italy