A precursor mission to high contrast imaging balloon system

Olivier Côté[a], Guillaume Allain[a], Denis Brousseau[a], Marie-Pier Lord[a], Samy Ouahbi[a], Mireille Ouellet[a], Deven Patel[a], Simon Thibault[a], Cédric Vallée[a], Ruslan Belikov[b], Eduardo Bendek[b], Célia Blain[c], Collin Bradley[c], Olivier Daigle[e], Chris de Jonge[l], David Doelman[d], René Doyon[f], Frédéric Grandmont[g], Micheal Helmbrecht[h], Mattew Kenworthy[d], David Lafrenière[f], Frank Marchis[i], Christian Marois[j], Steeve Montminy[k], Frans Snik[d], Gautam Vasisht[b], Jean-Pierre Véran[j], and Philippe Vincent[k]

[a]Center for Optics, Photonics and Lasers, Université Laval, Canada
[b]NASA Ames Research Center, United States
[c]University of Victoria, Canada
[d]Universiteit Leiden, Netherlands
[e]Nüvü Cameras Inc., Canada
[f]Université de Montréal, Canada
[g]ABB Inc., Canada
[h]Iris AO Inc., United States
[i]SETI Institute, United States
[j]NRC-Dominion Astrophysical Observatory, Canada
[k]Canadian Space Agency, Canada
[l]SRON Netherlands Institute for Space Research, University of Groningen, Netherlands

1. ABSTRACT

The HiCIBaS (High-Contrast Imaging Balloon System) project aims at launching a balloon borne telescope up to 36km to test high contrast imaging equipment and algorithms. The payload consists of a off the shelf 14-inch telescope with a custom-built Alt-Az mount. This telescope provides lights to two sensors, a pyramidal low order wave front sensor, and a coronagraphic wavefront sensor. Since the payload will reach its cruise altitude at about midnight mission, two target stars have been designated for observations, Capella as the night target, and Polaris as the early morning target. Data will be collected mainly on the magnitude of atmospheric and gondola's turbulences, the luminosity of the background. The whole system is already built and ready to ship to Timmins for the launch in mid-August 2018.[1]

2. INTRODUCTION

The advent of space-based astronomical observations has transformed the field of astronomy. However, all the advances of space-based observations come at a significant cost. A far cheaper alternative is to fly instrumentation aboard sub-orbital balloons which can be achieve at a fraction of the cost. HiCIBaS: High-Contrast Imaging Balloon System provides a platform to develop space-like imaging techniques. A high-altitude balloon can carry a telescope payload to a near-space environment, where high-contrast imaging experiments are possible.[1]

The HiCIBaS project consists of launching a 14-inch Schmidt-Cassegrain telescope (Celestron C14 XLT) mounted on an Alt-Az custom built mount. This telescope will be installed in a stratospheric balloon which is provided by the CNES and flown at an altitude of 36 km. At that altitude, there is only 1% of the atmosphere left to disrupt the light wavefront. It will provide light to an optical bench with the help of a tertiary Nasmyth-style mirror. This optical bench is composed of two instruments, first the Low Order Wavefront Sensor (LOWFS),

Further author information: (Send correspondence to Olivier Côté)
Olivier Côté: E-mail: olivier.cote.9@ulaval.ca

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and second a coronagraphic wavefront sensor (CWS). The LOWFS combined with a tip tilt mirror are used as a fine pointing stage as well as an instrument to measure the remaining high altitude atmospheric turbulences. The CWS combined to a deformable mirror are mainly used to correct the remaining aberrations in the system and to test new adaptive optics algorithms.[1]

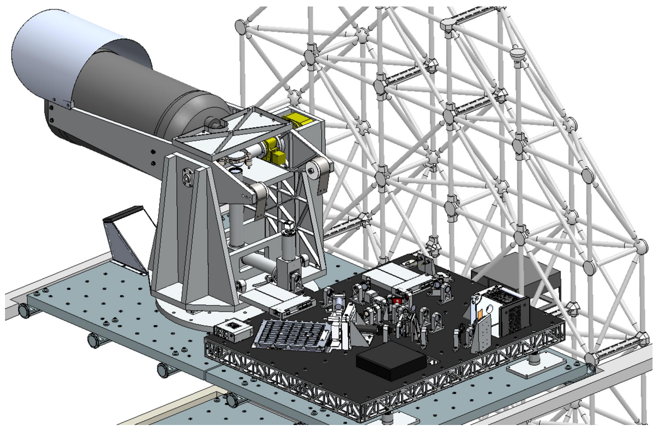

Figure 1. HiCIBaS complete assembly inside the gondola.

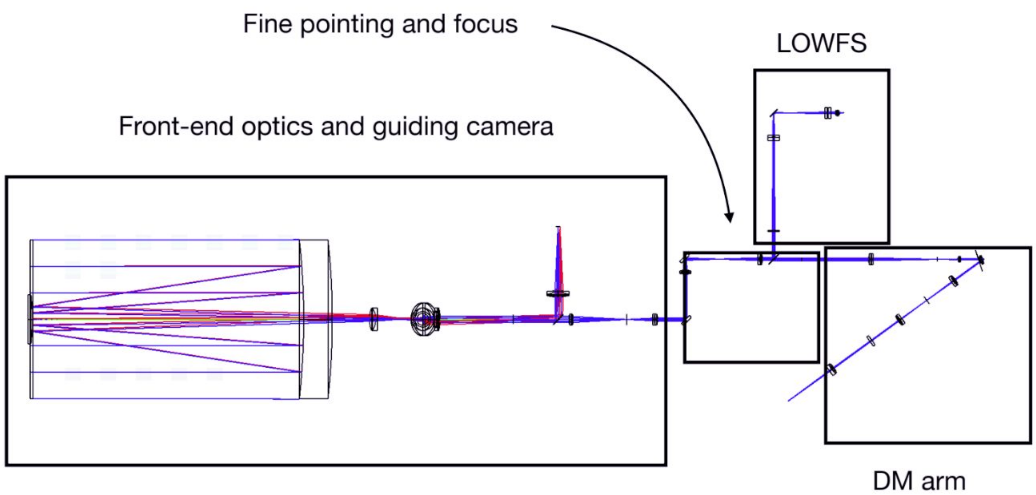

Figure 2. Optical layout of HiCIBaS.

In short, the objectives of this missions are to:

- Test the LOWFS on sky in high altitude conditions and Gather data on the high altitude atmospheric turbulences.
- Test AO components such as the DM and coronagraph in space like conditions.
- Test the pointing precision of the system (coarse and fine).
- Fly two Nüvü cameras (a HNü 512 and a HNü 128) in space like conditions.

HiCIBaS will be launched in Timmins, Ontario (Canada) on a specially converted airport by the Canadian Space Agency. HiCIBaS will be installed in the CARMEN gondola.[2] This gondola provided by the CNES can stabilize its azimuth rotation up to ± 1 deg. The launch date is between August 13^{th} and August 25^{th} just after 23h00. As shown on figure 3, the mission has two phases, the night and the day phase. During the night, Capella will be observed and all the instrument, LOWFS and CWS, will be tested. That star was chosen because first, it's a very bright star in the night sky, and second it stays between the range of the pointing system (0 to +60 deg) during the whole night. During the day, the objective will mainly be to get data on the luminosity of the background compared to our second target star, Polaris.

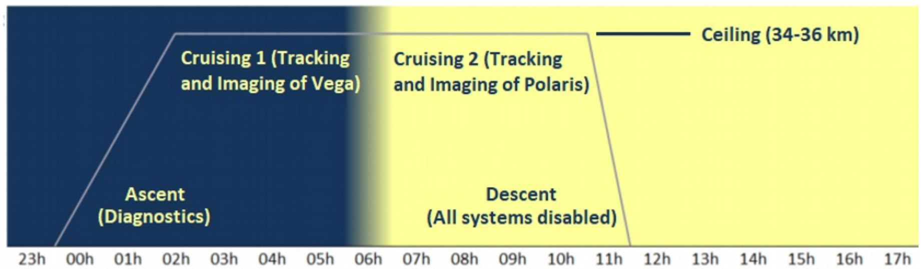

Figure 3. Mission Profile

3. COARSE POINTING SYSTEM

The coarse pointing system is responsible for localization of the telescope, and the correction of the oscillations of the gondola. This system is composed of an Alt-Az mount with a 3rd Nasmyth style mirror to redirect the light exiting the telescope to the optical bench. The Alt-Az mount and the optical bench were designed by the HiCIBaS team in colaboration with OMP inc. The mount can rotate the telescope ±20 deg in azimuth[1] to compensate for the gondola's pointing errors. In elevation, the telescope can move from -20 to +60 degrees.[1] It is unnecessary for the telescope pointing to go beyond +60 degrees because the balloon attached to the gondola would interfere in the path of the incident light. The -20 degree is required because the CSA demands that the telescope be placed in a safe and secure position for launching and landing phase. At -20 deg the telescope to be supported by the floor of the gondola.

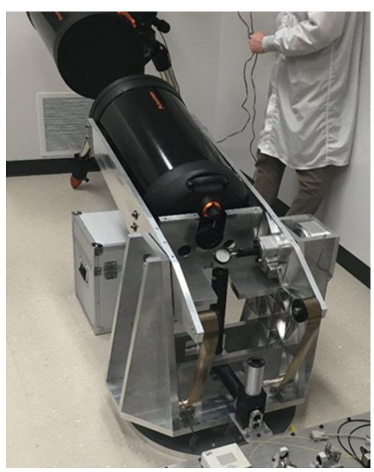

Figure 4. Telescope Mount.

To be able to tell precisely the orientation of the telescope, the system is equipped with a homemade star tracker. This star tracker is composed of a CMOS camera (IDS ui-3060cp rev. 2) 1/1.2 inch with a F1.3 50mm camera objective to provide an 8 deg by 5 deg FFOV. On sky tests shows that with this FOV, about 30 stars are detected with each frame. The on-sky precision of the star tracker is about 30as which is required to be able to direct the light of the target star to the main scope camera.

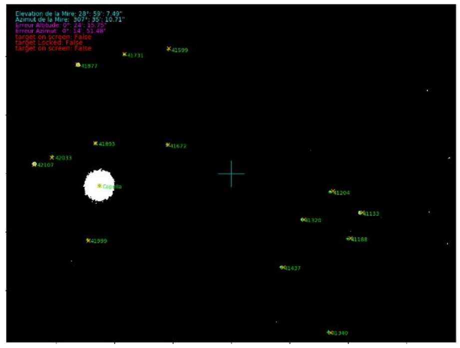

Figure 5. Example of the star Tracker image analysis results. Stars in the frame are identified by their catalog number. The azimuth and elevation of the telescope is also calculated from the image.

During the flight, the coarse pointing system must be able to stabilize the telescope up to ±5 as. As mentionned before, the telescope, it's a 14-inch F11.2 Schmidt-Cassegrain telescope (Celestron C14 XLT). Using another 1/1.2-inch CMOS sensor (ids ui-3060cp rev. 2), we can achieve a FOV size of about 360 as in each axis. To achieve that pointing precision, the main telescope camera resolution was chosen so that its resolution without subpixel considerations be about 0.4as. Also, to satisfy the precision criteria, all three chosen stepper motors for the mount have a step increment of 0.3as. Regarding the frequency of correction, according to the telemetry previous flight in 2015 at Timmins, the maximum turbulences frequency of the gondola is 0.65 Hz.

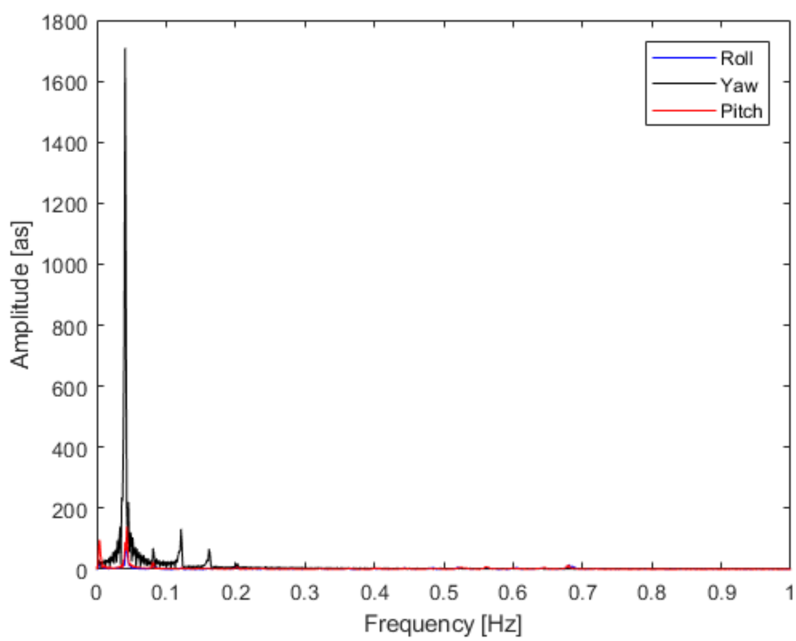

Figure 6. Amplitude and frequency of the gondola's turbulence. These data of a 2015 CARMEN flight were provided by the CSA.[3]

4. LOW ORDER WAVEFRONT SENSOR

As previously mentioned, the Low Order wavefront sensor (LOWFS) as two usages. First, it is used to measure the tip, tilt and defocus of the HiCIBaS system and correct it using a piezo electric tip-tilt mirror. In other words, it serves as the fine pointing stage of the system. The other usage of the system is to measure the high altitude atmospheric turbulences. Regarding that last aspect, the sensor was tested at the Observatoire du Mont Mégantic in Canada. The results were presented by Guillaume Allain at the SPIE Astronomical Telescope + Instrumentation.[4]

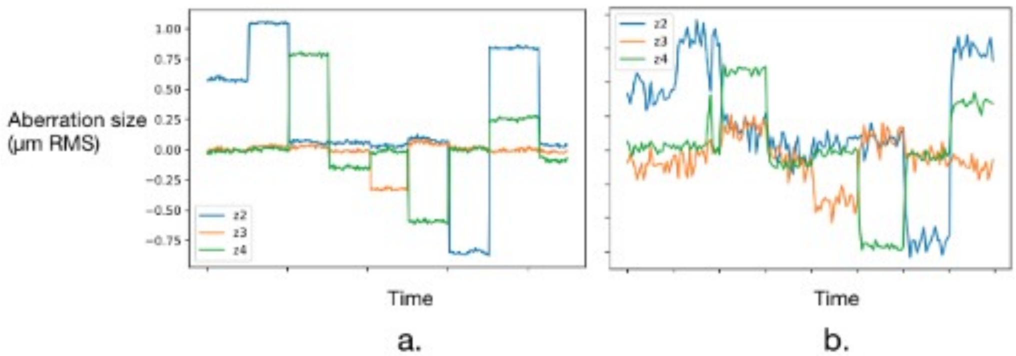

Figure 7. Results of the aberration reconstruction test at l'Observatoire du Mont Mégantique with A) a laser source and B) the on-sky observation.[4]

As shown on figure 5, the sensor is composed of an axicon, a pyramid, and a Nüvü HNu 128 EMCCD camera. This system works with lights with wavelengths ranging from 509nm to 800nm. For this sensor an axicon is used because of the problem usually encountered with the tip of the pyramid. An optical pyramid always has a defect at the tip, and this tends to reduce the performance of the overall sensor. By passing collimated light in an axicon first, the negative effect of the tip of the pyramid is mitigated because almost no light pass through it.[5] As the fine pointing stage, this subsystem is expected to correct the remaining pointing error of the telescope to about 50mas.[1] This pointing accuracy is required so that the coronagraphic arm can properly retrieve wavefront aberrations information as well as produce high contrast image of the surroundings of the star.

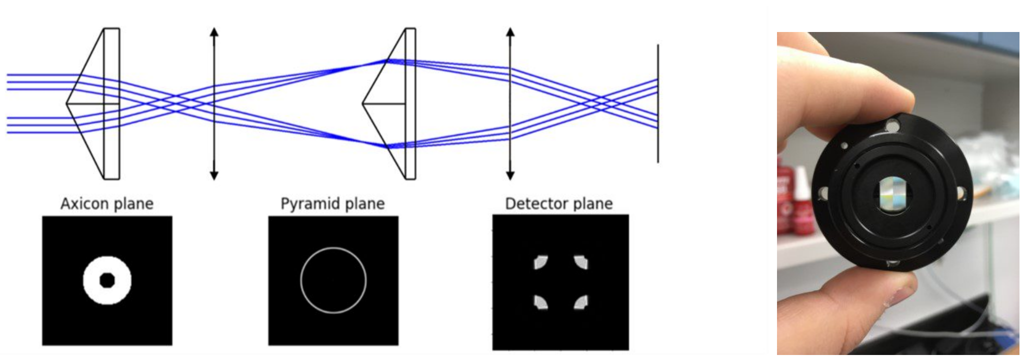

Figure 8. Low order wavefront sensor schematics and the pyramid currently used in the project.

5. CORONAGRAPHIC ARM

Finally, the last part of the HiCIBaS system is the Coronagraphic Wavefront Sensor (CWS) which uses the wavelength band between 817nm and 867 nm. The optical design shown at figure X presents the three main components of the system which are the deformable mirror (DM), the coronagraph phase mask and finally the science camera.

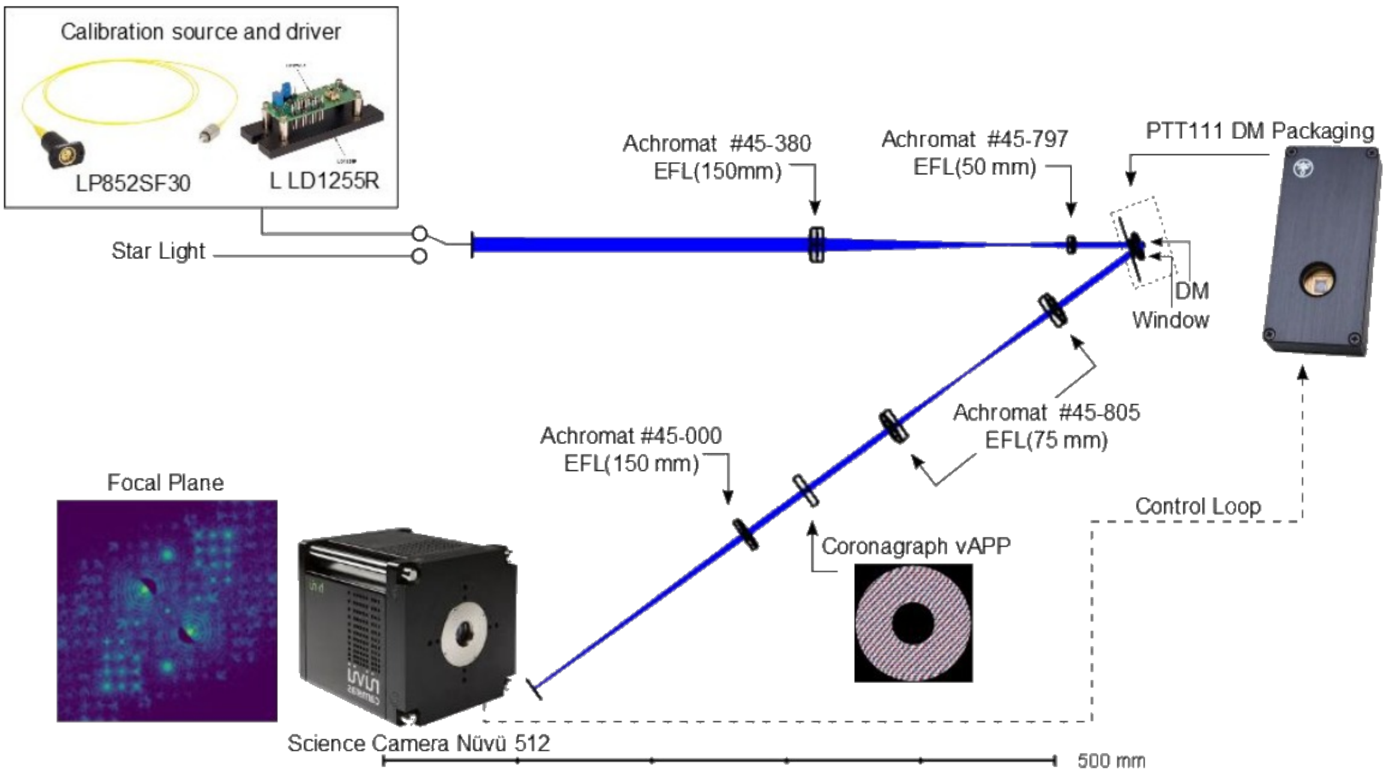

Figure 9. Coronagraphic wavefront sensor schematic as used on HiCIBaS.

Provided by our collaborator Iris AO, the deformable mirror is made of 37 hexagonal segments and allows the wavefront correction of the 20 first Zernike terms. The coronagraph phase mask is designed at the University of Leiden in Netherlands and has two main functions. The phase pattern allows coronagraphic imaging by blocking the light of the star and induces phase shifts needed to retrieve the wavefront error coefficients in the focal plane. By decoupling the two circular polarizations, the mask creates two holographic copies of the science PFS into the field of view (FOV) of the science camera. More precisely, it creates a pair of holographic copies for the dark hole image and for each Zernike modes. The measure of the wavefront aberrations is given by the difference of intensity between a pair of copies. The design choose for HiCIBaS mission is presented at figure 2 and contains three unchanged science PFS, two dark hole and 12 Zernike coefficients.

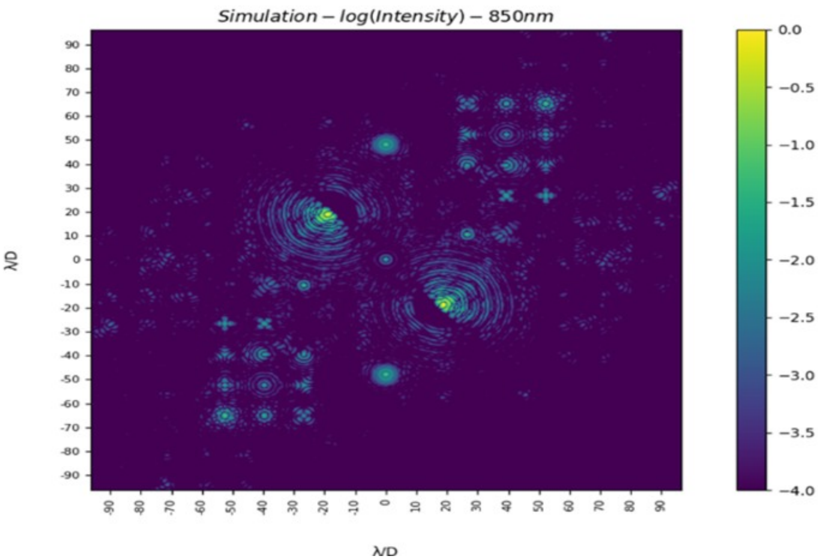

Figure 10. Image produced by the coronagraphic mask.

Since the science PFS stay unchanged in the focal plane, only one camera is needed to retrieve simultaneously the science image and the wavefront aberration information. This configuration eliminates the non-common path errors that is usually an issue in more conventional adaptive optics designs because of the optical path difference between the wavefront sensor and the science camera.[6] This feature also simplifies the optical design and helps to reduce the power consummation needed during the flight.[6]

The camera chosen for the high-contrast imaging is a Nüvü512 EMCCD camera combined with a prototype space controller. It has the particularity to allow an EMGain mode that enhances SNR for low light imaging conditions. Over all, the coronagraphic wavefront sensor will correct static wavefront error remaining in HiCIBaS system and try to achieve the best contrast for the dark hole.

6. CONCLUSION

To conclude, the HiCIBaS aims at demonstrating of that space-like quality imagery is possible on a stratospheric balloon plateform. The system is a composition of three subsystems: the telescope and mount for the coarse pointing, the low order wavefront sensor for fine pointing and sensing and the coronagraphic arm to produce high contrast images. Each subsystem works with a distinct section of the visible and NIR light.[1]

The system will be launched in mid-August at Timmins in Canada where it will perform an 8 hours mission divided into the night phase and the day phase. Observations during the night will tests every subsystem whereas observations during the day will probably use only the coarse pointing system to measure the background level of the sky.[1] The goals of the flight are to test the LOWFS on sky in high altitude conditions and gather data on the high altitude atmospheric turbulences, to test the pointing precision of the system (coarse and fine), and finaly to fly two Nüvü cameras (a HNü 512 and a HNü 128) and AO components such as the DM and coronagraph in space like conditions.

The next step (HiCIBaS-II) will be to develop and test a complete coronagraph for high-contrast imaging, test a high-resolution deformable mirror and run a fast closed loop AO system at 36 km, measure and gather data on the contrast ratio in various conditions using the Nüvü EMCCD camera. This work is supported by the

FAST program, granted by the Canadian Space Agency (CSA). This grant gives an opportunity to train highly qualified personnel by supporting projects involving students and young researchers. Furthermore, the flight will be part of the STRATOS program from CSA which gives academic and industrial projects a way to perform scientific experiments at stratospheric altitudes using balloon flights. This provides a way for small teams to test new equipments and novel experiments in near space conditions.

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