Vacuum technology as a vital support for astronomy

Jean Louis Lizon, ESO, Karl Schwarzschield Str 2, D 85748 Garching bei München

Abstract

If astronomy is one of the oldest sciences it has been very long time practiced by very motivated scientists with very little technical support. The starting of the four-meter class telescope in the 60's was a first step toward an involvement of the industry.
From the 90's, the construction of the very large ground based facilities has only been possible through a challenging cooperation of all high technology industries.
Vacuum technology, mainly associated to cryogenics, is one of the keys to an optimal operation of the eyes of the Very Large Telescope. Optical detectors, as well as complete infrared instruments require a very low temperature in order to perform optimally on the extremely faint astronomical objects.
After a short presentation of the VLT, the world largest astronomical facility of the European Southern Observatory (ESO), the presentation will point out the various important fields of applications of vacuum technology. Based on concrete examples, a detail analysis of the very strong requirements will be presented.
The conclusion describes the ideal pumping system for the future gigantic telescope and its instrument clusters.

Introduction:

ESO the European Southern Observatory has been founded in 1962 in order to provide the European astronomical community with an observation facility in the southern hemisphere. This was concretized with the construction of the La Silla observatory in the south extremity of the Atacama desert in Chile. This observatory was still developed until the early 90's to host a total of 13 Telescopes of different sizes from 0.5 m up to 3.6 m. The optical observing capacity is completed with a 15 m radio antenna.
These telescopes are equipped with various instruments, which are installed, after preparation, at the telescope for one to two weeks observation campaigns.

Figure 1 shows an overview of La Silla observatory

A new era started in 1987 with the approval of the Very Large Telescope (VLT). This is the world's largest astronomical facility. Beside the four 8 meter telescopes the facility includes a large interferometer which can either be fed by the main unit telescopes or with four 2 meter movable auxiliary telescopes. The coherent interferometric focus is fitted with a palette of infrared instruments while every of the three foci of each unit telescope is fitted with instruments covering in total the wavelength range from the UV (0.40 µm) to the mid infrared (25 µm).

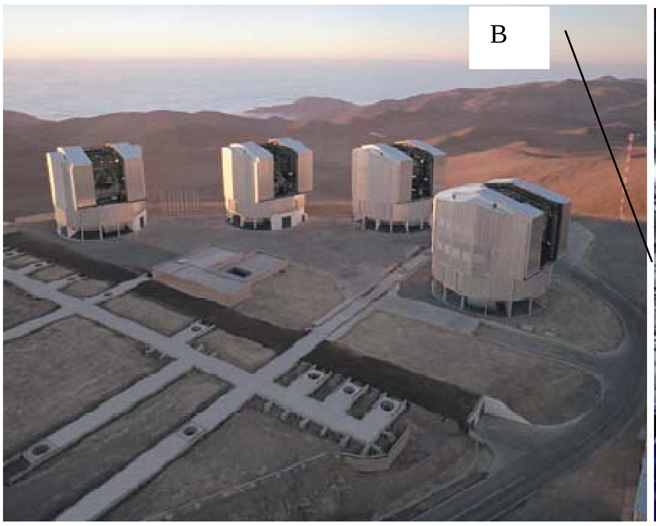

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Figure 2: overview of the VLT platform

Figure 3: VLT unit telescope

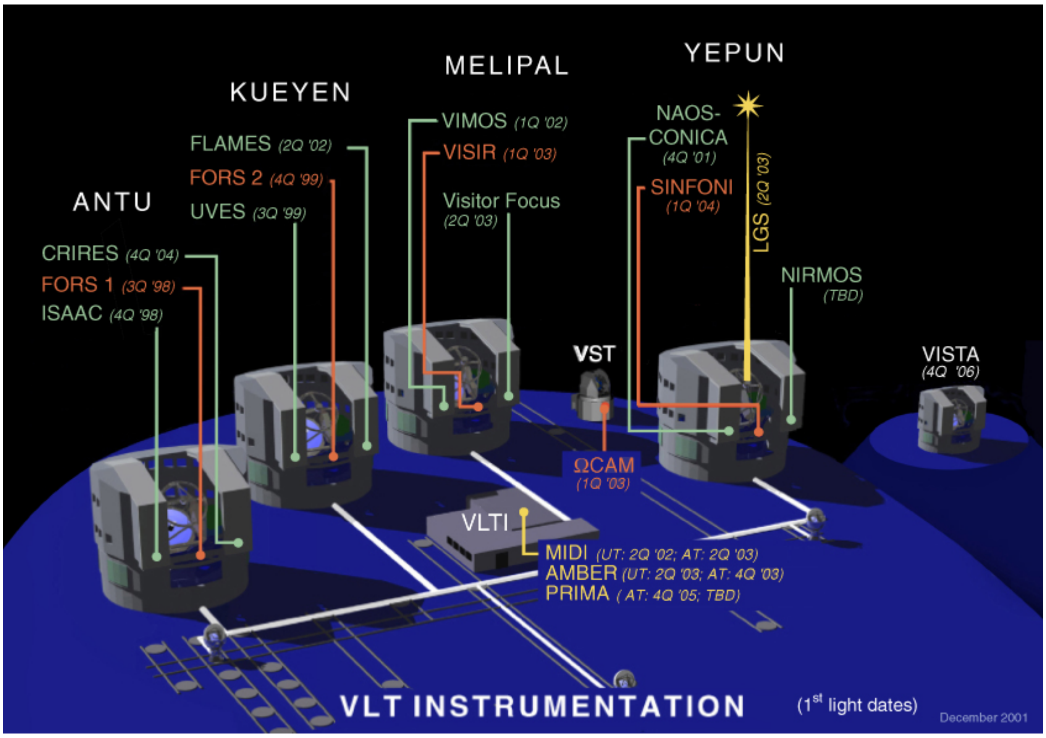

Figure 4: Overview of the VLT observatory with its instruments

The VLT is located on the mount Paranal in the heart of the Atacama Desert in the northern part of Chile and what is believed to be the driest area on Earth. Cerro Paranal is a 2,635-m high, about 120 km south of the town of Antofagasta and 12 km inland from the Pacific Coast. This site in the Andes is also subject to often rather strong earthquakes.

To have the instruments permanently operational is one of the major changes introduced in the VLT observatory. This led to the need for very high reliability (high Mean Time Between Failures) but also very low allowed preparation time. This is even more significant as, due to its geographical location, the VLT is operated with a very small staff complement.

The instruments can be split in four main categories depending on their location:

- Cassegrain focus instruments (A): They are directly attached onto the telescope ‘tube” below the primary mirror. For this reason these instruments are subject to strong weight restriction but also to very strong environmental requirements (low thermal dissipation, very low vibrations..). During operation they are following all telescope movements (azimuth, elevation) and field rotation compensation.
- Nasmyth focus instruments (B) are also mounted on the telescope, being attached onto the telescope fork via what is called the adaptor. This type of instrument is also subject to the similar type of requirement than the previous one. During operation they are following the azimuth rotation of the telescope and they are rotating around an horizontal axis to compensate the field rotation.
- Nasmyth platform instruments are resting on a 6 m x 8 m platform which is attached onto the telescope fork structure. If they are subject to the same vibration and thermal requirement as the Nasmyth focus instrument, these instruments benefit from a considerably relaxed weight restriction. In operation they are only submitted to the slow telescope azimuth rotation without any gravity change.
- Interferometry instruments are laboratory instruments directly resting on the ground of the laboratory. They are submitted to strong vibration and thermal dissipation restrictions.

Vacuum applications:

Mirror coating facility

It is not possible to address the subject of vacuum application in an observatory without mentioning the best known: the coating facility for the telescope’s mirrors. Here also the VLT opened a new challenge with the need of a coating chamber, which could host an 8-meter mirror.

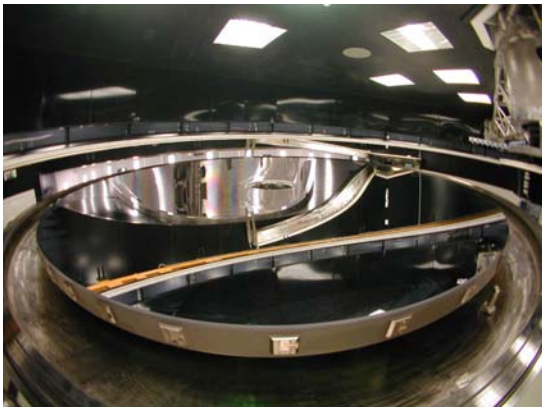

Figure 5: Primary mirror right after aluminization

Figure 6: Preparation of small mirrors in the chamber

The primary and tertiary mirrors of the telescope are re-coated every 18 months while the secondary, that is less exposed (looking down), is refreshed only every 4 years. The chamber has a total volume of 130 m^3 and is evacuated to a pressure of 10^{-6} mbar within 8 hours before the coating process starts. A battery of 8 cryogenic pumps backed with two rotary-vane pumps and one Root's pump is used to achieve this.

Figure 7: Overview of the coating facility with in the background the lower part of the vacuum chamber

Optical detectors

The CCD (Charge Coupled Device) detectors have since long completely replaced the traditional photographic plate from the early days. In order to operate with optimal performance these detectors need to be operated at temperatures between 120 and 150 K. For this reason the detectors are enclosed in a vacuum vessel and heat sinked with nitrogen bath cryostats, nitrogen continuous flow or Joule-Thomson coolers depending on the application.

If a residual pressure of 10^{-3} mbar would be largely enough to provide a reasonable thermal insulation, the detector systems have to be operated at much lower pressure in order to avoid any contamination of the sensitive surface of the chips. In its environment, the detector chip is rather exposed, operated at low temperature (around 120 K), it is directly looking to the warm blackened window surrounding area. Practical experience has shown that under these conditions, even at a 10^{-6} mbar residual pressure, a contamination deposit appears on the detector already after a few weeks (see figures 8). The molecular layer, mainly composed of water, acts then as an optical filter cutting mainly the blue radiations. The consequence is an unacceptable loss of efficiency in the short wavelength range. The problem has been mostly solved by the application of a systematic baking procedure of every cryostat.

This extreme sensitivity of our detectors, even if there are very few cases where irreversible damages have been registered, justifies the various precautions taken in order to prevent any dangerous situations:

- Every detector system is of course fitted with a cold sorption pump, which keeps the vacuum during operation.
- Only fully dry pumping systems are used to produce the original vacuum.
- Every detector system is fitted with an emergency pumping system which starts automatically in case of pressure rise (vacuum leak or failure of the cryogenics system).

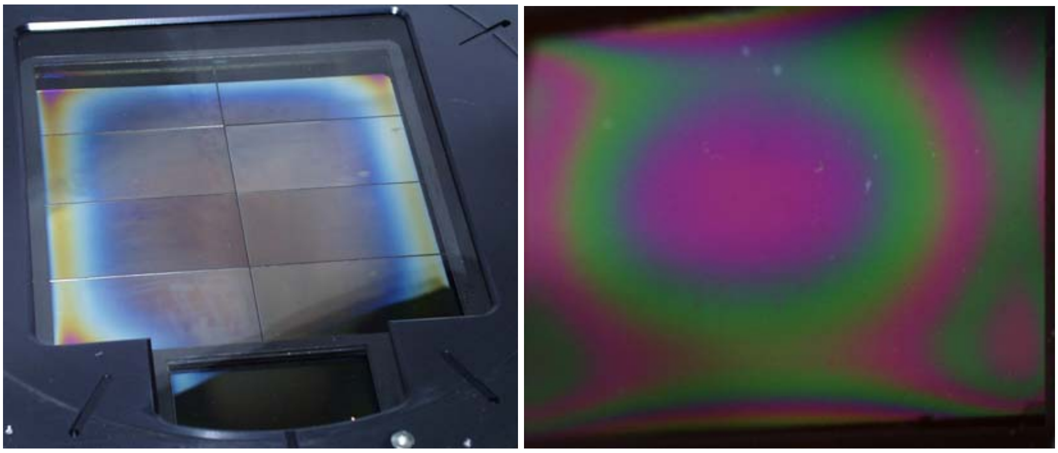

Figure 8: Contaminated CCD chips

Figure 9 shows the schematic of a standard detector system cooled via a continuous flow of liquid nitrogen. The various heat exchangers are represented inside the vacuum envelope. Outside we can see the pumping system. An electro-magnetic valve, on the molecular flow, seals the cryostat. In case of a problem, the vacuum gauge commands directly the operation of the pump and the opening of the valve. This heavy valve could be replaced by a smaller valve in the viscous flow in the case of the use of a perfectly clean pump. During the months and the years of operation, the very small amount of lubricant in the bearing of the TMP would be sufficient to contaminate the cold detector.

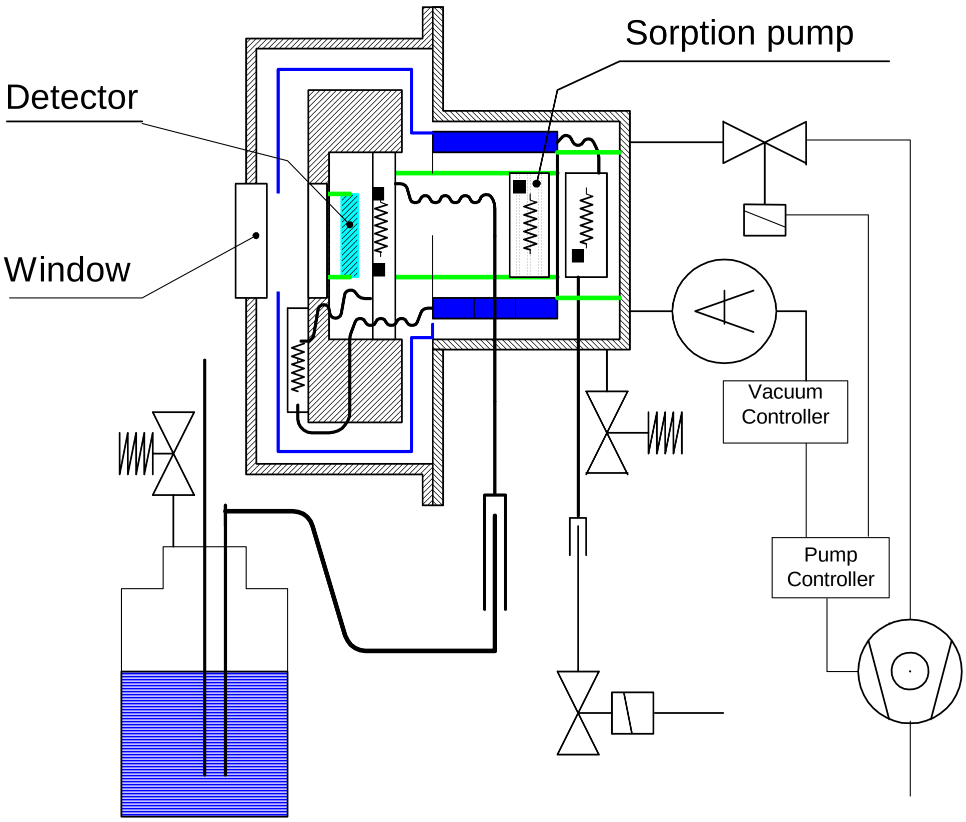

Figure 9 : Schematic of a CCD cryostat system

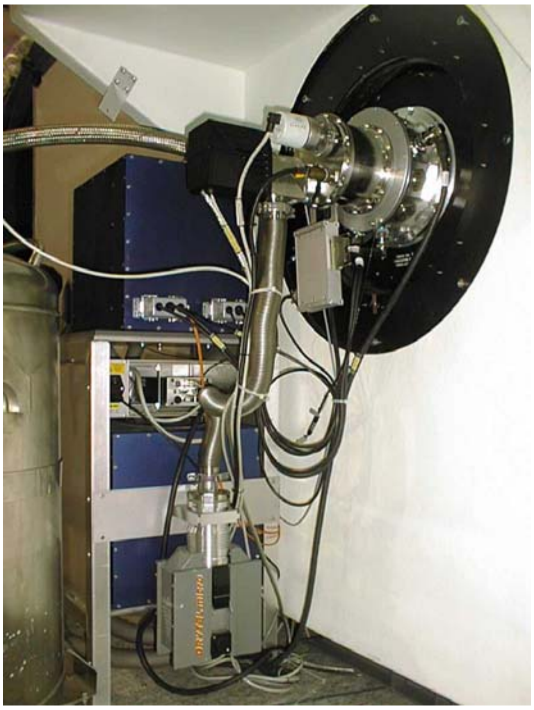 

Figure 10: Two applications of CCD cryostat system

Infra Red Instruments

In the last decade with the end of the cold war, infrared detector arrays, which were until then under military control became suddenly available for civil application. This together with the rapid progress of the technology and the ability to produce increasingly larger arrays, did provoke the real start of the IR astronomy.

The two photographs below illustrate clearly the large interest induced by the IR astronomy. It allows not only to see “cold” stellar objects (planets) but it also in some circumstances allows to see through dust or gas clouds.

 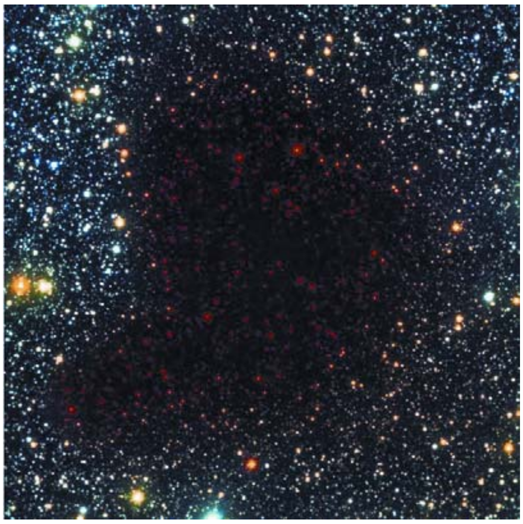

Figure 11: A stellar field seen in the visible (left) and in Infra Red (right)

In order to reduce as much as possible instrumental background, infrared instruments are cooled to cryogenic temperatures. Depending on the wavelength range of operation, the temperature varies from 80 K (for the 1-5 µm wavelength range) to 20 K (for the 8-25 µm wavelength range). The complete instruments: optics, mechanical structure and mechanism are enclosed in large (up to 3 m^3) vacuum vessel and cooled down to these temperatures. The recommendation and care discussed before concerning the detector systems applies also in this case even stronger in the sense that many optical surfaces would be affected in case of a contamination.
Due to the manufacturing technology and more especially to the hybridization of many layers the IR detectors are much more sensitive. Permanent damage has already been recorded.
Figure 12 shows the schematic of the vacuum system for a large IR instrument. A powerful pumping system is used to evacuate the instrument within 5 hours to a pressure as low as 10^{-5} mbar. This very rapid evacuation time is imposed in order to reduce the turn over time in case of intervention. The original pumping system is mainly composed of a 300 l/s magnetic bearing turbo molecular pump backed with a 20 m3 /h dry pump. In order to exploit fully the large pumping capacity, the TMP is directly flanged onto the vessel. The extreme cleanliness of the pump allows the suppression of the very heavy and complex operable valve on the molecular flow. This pumping system is used to produce the original evacuation and every year to regenerate the sorption pump. The sorption pump, three plates covered with activated charcoal operated at 60 K is located just in front of the evacuation port in regard of the TMP. This has the advantage to allow a regeneration even if the full instrument is kept cold and without risk of contamination. It has also the advantage to pump directly the rest gas in the back stage of the turbo while closing the insulation valve.

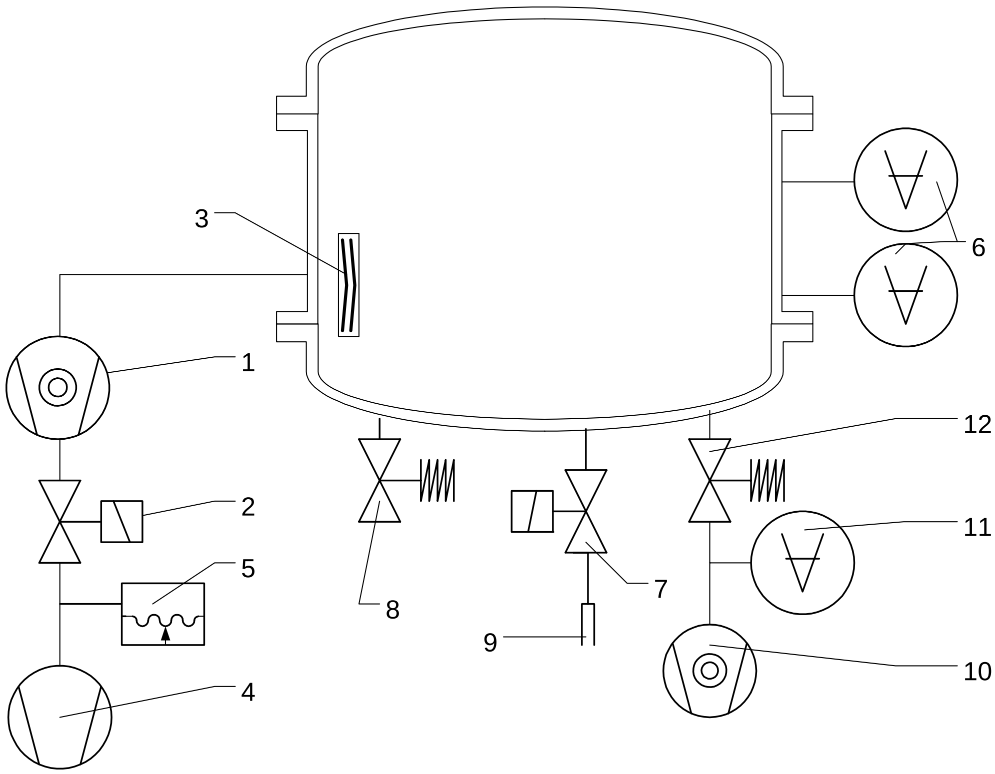

Figure 12: Vacuum schematic of a large IR instrument

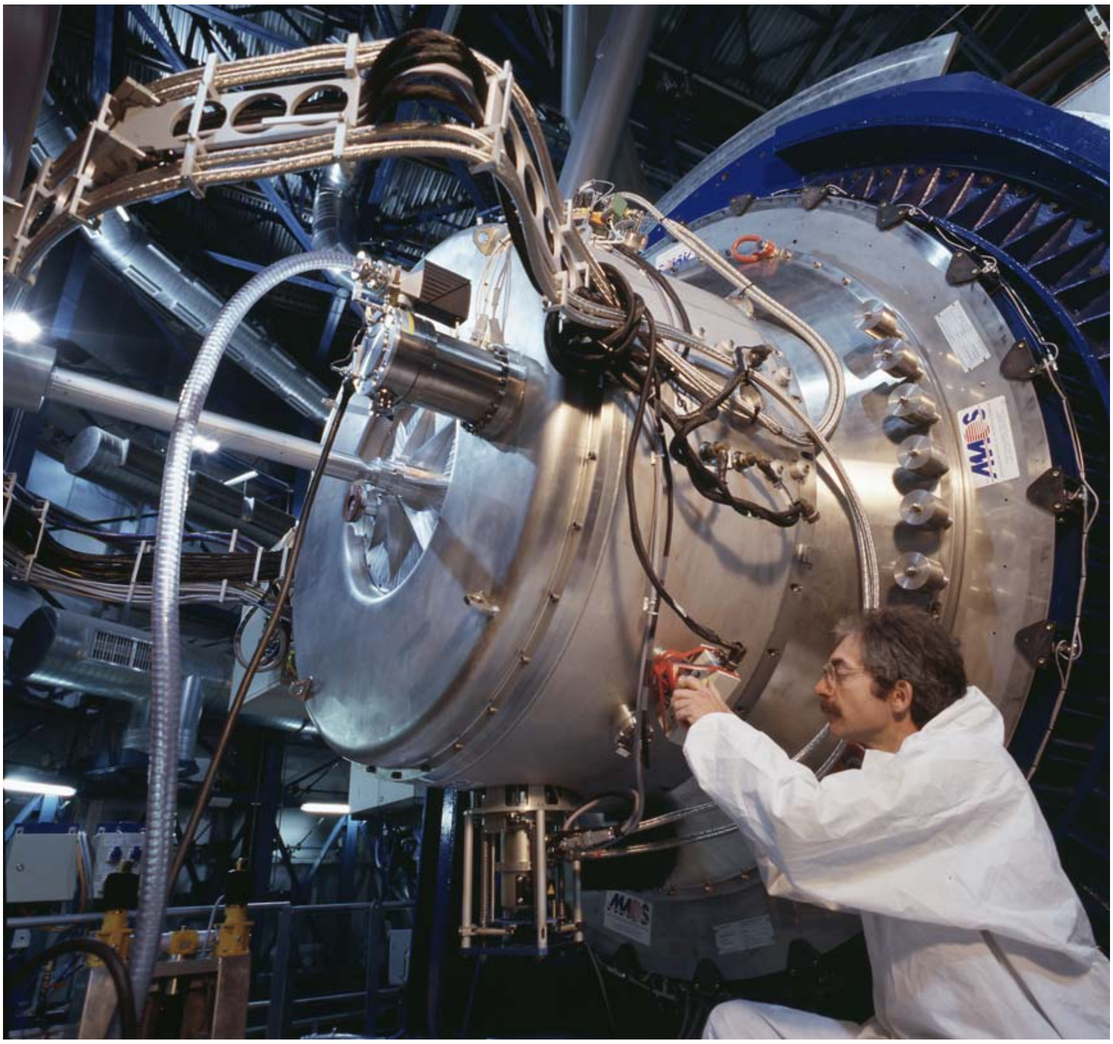

Figure 13: ISAAC one of the largest IR instrument in operation at ANTU

The instruments are kept cold using Joules Thomson Closed Cycle Coolers. A power failure might have some disastrous consequences and directly lead to a contamination of the detector. In order to limit the risk a small dry pump supplied with a local battery is used to keep a reasonable vacuum during the time required to heat up the very sensitive and very expensive detectors such that it is not any more the coldest point.

Very high stability spectrograph

Extra-solar planets can presently only be detected through indirect observation. One way is the very accurate measure of the small variation of the radial velocity of the star caused by the rotation of the satellite. This is only possible with an extremely stable spectrograph over periods of a few months. Typically the mean position of the stellar lines is to be measured with an accuracy of 1/1000 of a CCD pixel (15.4 µm). Enclosing the complete spectrograph in a vacuum helps to keep it thermally stable, but also to reduce the variation of the optical characteristic of the medium in which it is operating.

Figure 14 shows HARPS. The instrument is enclosed in a 3 m^3 tank which is operated at a pressure between 10^{-2} mbar and 10^{-3} mbar. A 100 l/s pumping system linked to the vacuum gauge is operated from time to time during the day to refresh the vacuum.

Figure 14: The High Accuracy Radial velocity Planetary Search Project (HARPS)

Conclusion:

The VLT counts 12 foci, which are all equipped with either cryogenically cooled instruments or instruments using up to four cryogenically cooled detectors. ESO is currently assembling the two last of the first generation of instruments. Plans for second generation instruments have been elaborated and equally rely on cryogenic systems.
It is now the right time to define the vacuum systems of the future which are going to equip the second generation of instruments and in a longer future the very complex cluster of instruments of the gigantic OWL telescope.

General environment constraints:
Operation at > 2500m above see level, at temperature from 0º C to 20º C with low sound level (< 40 dBA), no recordable vibration below 5 Hz maximum of 5 peaks at 0.1g for the band 5 to 200 Hz.
The operation should not be affected by strong earthquakes: 5 Richter
Motion conditions: Rotation from 0.1 deg/ min in tracking up to 5 deg/ min in pointing. Max acceleration: 1 deg. S^{-2}

For detector system
Magnetic bearing TMP, pumping capacity 3 l/s, pressure limit < 10^{-6} mbar, maximal weight 1.5 kg.
Dry pre-vacuum pump without emission of particles, pumping speed 10 m^3/h, maximal weight 2.5 kg.
The complete system should consume less than 30 VA and dissipate less than 2 Watts.

For IR instruments
Magnetic bearing TMP, pumping capacity 300 l/s, pressure limit < 10^{-8} mbar, maximal weight 6 kg.
Dry pre-vacuum pump without emission of particles, pumping speed 30 m^3/h, maximal weight 8 kg.
The complete system should consume less than 100 VA and dissipate less than 6 Watts.