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Ministry of Education
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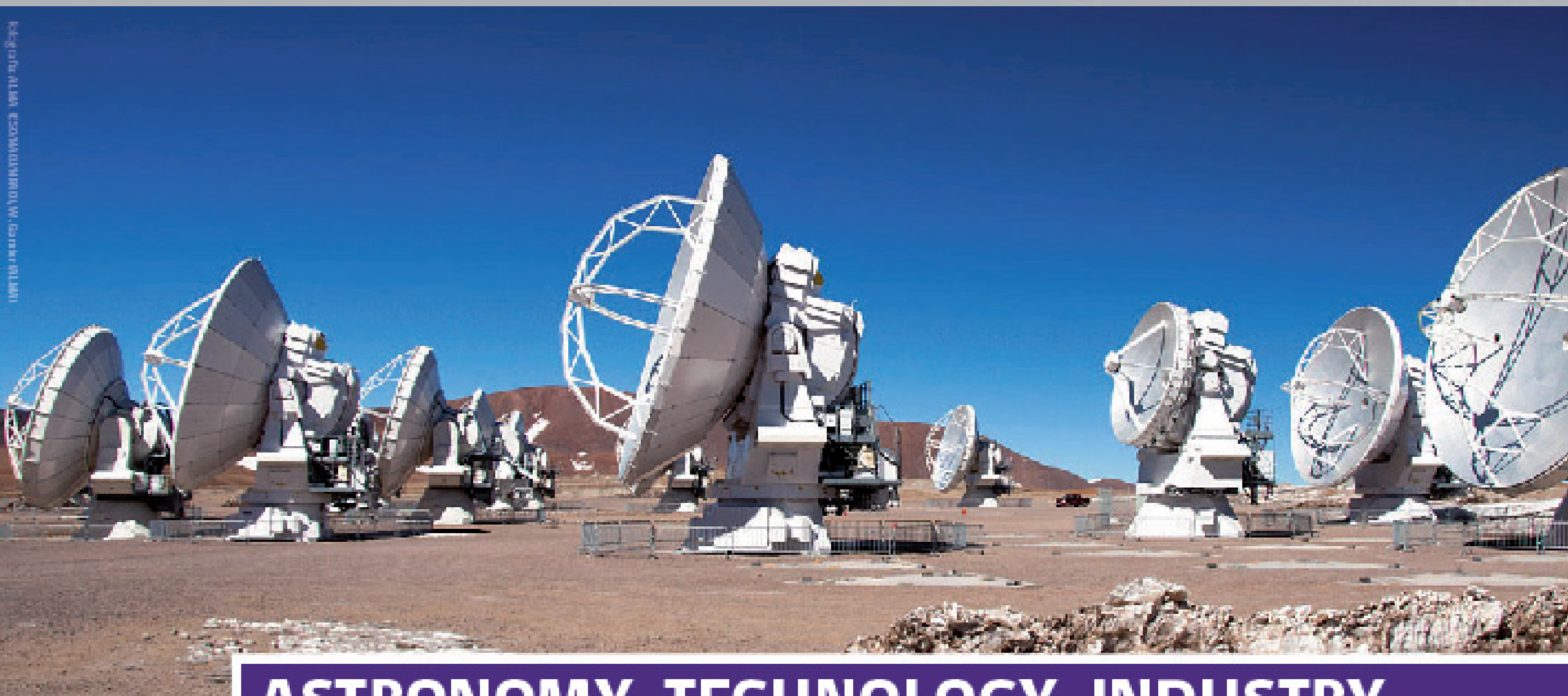
ASTRONOMY PROGRAM



ASTRONOMY, TECHNOLOGY, INDUSTRY

Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile

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NEW CHALLENGES FOR THE DEVELOPMENT OF ASTRONOMY IN CHILE

The excellent quality and transparency of the skies of northern Chile have attracted the installation of international astronomical observatories in the world. By the year 2020, Chile will concentrate over 70% of the world's astronomical infrastructure; the most powerful telescopes ever built will be installed in the country, representing an investment of about 6 billion dollars.

Astronomers in Chilean institutions have access to 10% of telescope-time on each of these instruments, thanks to agreements signed with the organizations operating them. Consequently, astronomers in our universities have a unique opportunity to compete successfully at an international level, making astronomy the science with the highest impact and international presence in Chile. Our country has the possibility of becoming a major player in world astronomy.

Astronomy requires sophisticated and complex telescopes and instruments for the study of the universe. Every new telescope or detector is an innovation on instrumentation and represents a major technological challenge. The governments of the countries that fund these international observatories invest increasingly in new telescopes and detectors. In this way they support technological development and innovation in frontier technologies in areas such as engineering, materials, control systems, software development, new processes. These developments are done with their industries, which benefit from technology developments efforts and create spin-offs that will make them and their respective countries more competitive.

CONICYT, along with CORFO/Innova and the Innovation Division of the Ministry of Economy, took the challenge in 2011 to look into ways in which our country could use astronomy as an ecosystem for technological development and innovation in addition to the high impact of its astronomical research. This was done by establishing a working group coordinated by the Astronomy Program of CONICYT and by hiring two international experts. An invitation to join this working group was sent to the Innovation Council for Innovation and Competitiveness (CNIC) and the Ministry of Foreign Affairs, Directorate of Energy, Science, Technology and Innovation (DECITY).

The consultants were charged to preparing a report with recommendations and suggestions on how to address this challenge. These recommendations should have short and medium term actions that the agencies involved could consider as a basis for the development of a national strategy.

The working group and the recommendations are summarized in the present document, "Astronomy, Technology and Industry: Roadmap for the Fostering of Technology Development and innovation in the field of Astronomy in Chile"

CONICYT would like to thank all participants in this work. In particular, the support and contribution of all members of this working group, the astronomers, engineers and scientists in the universities, the international observatories and their representatives and staff as well as the industry representatives that contributed with their time and input to this effort. We consider this document as an initial proposal to the development of a national strategy to develop an ecosystem of innovation and technology in the field of astronomy and astro-engineering.

Chile is well known today in the world for its copper. Around this activity it has developed knowledge and service companies that have allowed the country to be a respected player in mining. The sky of Chile is a precious world resource also attracting large foreign investment and thus giving us another opportunity to position ourselves in a place of leadership. CONICYT is committed to supporting and promoting the development of national astronomy, to protect this valuable resource and to work together with other agencies in the country in the efforts that this challenge requires. Our endeavor is to enter a new stage where in addition to having a strong scientific research capability, the country can gradually undertake new challenges and evolve into an ecosystem of development of technology and innovation related to the field of Astronomy.

Mónica Rubio PhD.
Director
Astronomy Program
CONICYT

ASTRONOMY, TECHNOLOGY, INDUSTRY

Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile

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Executive Summary

The skies over Chile are well recognized as a global natural resource for astronomy. How can this natural resource best benefit Chile? To be sure, the presence of so much of the world's telescope inventory already benefits Chile with prestige and an ever growing community of international scientists. Astronomy appears frequently in the Chilean media. Astronomy and its community have become part of the cultural tapestry of modern Chile. Looking ahead, nearly 2/3 of the world's telescope light collecting area in the visible and infrared wavelengths may soon be located in northern Chile and Chile already hosts the highest sensitivity collecting area in the millimeter and sub-millimeter radio bands. It is imperative to ask how this global asset, located in Chile, can be leveraged beyond global astronomy to benefit Chilean science, education, industry and development. Furthermore, is there a path by which Chile can leap beyond incremental gains in leveraging this asset to leap frog into the front ranks of global astronomy technology and innovation. Chile can seek to leverage its many international observatories to strengthen general education, or science, technology, engineering and mathematics (STEM) education. Chile may act to stimulate Chilean astronomy itself. Industrial development can occur through captured innovation, elevation of skills and engineering challenges within Chilean industry and expansion of the service industries supporting the observatories. Chile can move into a more collaborative posture with international observatories and with international firms leading technology delivered to observatories in Chile. All of these thrusts are advantageous to promoting Chile's advancement through its clear skies natural resource.

However, we recommend that, in order to advance Chile in **indigenous** science, technology and innovation, Chile should follow a roadmap to develop native scientific and technological leadership in one or two carefully selected technology areas at the core of astronomy research by Chilean astronomy and engineering groups, applicable at the international observatories hosted by Chile. This strategy is recommended in order to leap frog Chilean science, technology and innovation to world class rank within a decade.

This recommendation is complementary to other recommendations currently under consideration that urge attraction of foreign industrial presence and closer collaboration with programs of the international observatories. These will advance Chilean benefits incrementally and are of significant benefit. We focus our recommendation on a more direct thrust to build outward from Chilean astronomical interests, to start at the root of innovation ecology and to make a rapid step to a leading position in global astronomy technology.

A bit more than a year has been spent by an interagency cooperative effort to develop a Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile. In May 2011 the National Commission for Scientific and Technological Research (CONICYT) formed a working group charged to evaluate current capabilities in Chilean industry and universities related to producing technology with applications in astronomy, and to provide recommendations to boost such activity in Chile.

This Roadmap Working Group included the participation of officials from CONICYT (Astronomy Program), the Ministry of Economy, Corfo/InnovaChile and international advisers Dr. Gary Sanders (Project Manager for the Thirty Meter Telescope Project, USA) and Dr. Angel Otárola (Scientist at the Thirty Meter Telescope). In addition, the working group membership was complemented by participation of staff from Chile's National Innovation Council for Competitiveness, and from the Directorate of Energy, Science, Technology and Innovation (DECITY) at the Ministry of Foreign Affairs.

Stakeholders including Chilean university groups, international observatories, industries and industry associations were surveyed and interviewed and the results of these studies are summarized in this Roadmap. Related studies were carried out in parallel by the Ministry of Economy and significant information and input has been shared.

We argue that the creation of one or two Chilean initiatives to lead the development, delivery and use of world-class science instrumentation in these observatories has the potential to rapidly and significantly boost indigenous development of technology in Chile. In addition to other initiatives that may involve education, commercial stimuli, or creation of high technology industrial capabilities, we advocate that a key step in leveraging Chile's position is accomplished by staying close to the observatories' program needs and **positioning the Chilean astronomy community to lead in meeting some of those needs.** This can lift the Chilean astronomy community onto the world stage of astronomy engineering (astro-engineering) and innovation, and bring the Chilean astronomy community to the next level. It will be the first piece of any industrial ecology that seeks to leverage astronomy in Chile. A stimulus to Chilean astronomy does not depend only upon partnering with the international observatories or the industrial sector at the start but all efforts to strengthen links among these actors is obviously a must and should be encouraged.

As a frontier basic science, astronomy employs advanced mathematical, analytical and technical methods. The instrumentation of astronomy requires optics performing at the nanometer level, precision guiding, advanced multiple-input, multiple-output controls systems, comprehensive spectroscopy, imaging, interferometry and array phasing at all wavelengths, precision opto-mechanics, cryo-cooling, facility-scale software environments and systems, and large-scale distributed system integration. These techniques, methods and technologies underpin astronomy, can be used for example in mining activities, medical, meteorological, and others, but they are also crucial to assuring the national defense. Furthermore, the scientific and technical workforces needed to design, deploy and exploit these technologies and methods are prerequisite to realizing these technologies within Chile. Leveraging the presence of international astronomy in Chile creates university, industrial and human capital assets of great advantage to the Chilean defense sector, as is the case for OECD countries. Similarly, the defense sector in Chile may possess advantageous capabilities for astronomy in Chile.

Among our principal recommendations, we urge increases or creation of new funding opportunities at levels higher than existing funding programs in astronomy projects of world class significance. Present funding levels provide for laudable but modest development. We recommend that Chile create the conditions to step onto the world stage in astronomy and its seminal technology.

It is essential that this initiative be firmly based on a science vision that is developed and embraced by the Chilean astronomy community. The very first significant step should be to commission a one-year long "decadal survey" of astronomy by the Chilean community. This study should call for a prioritized report of the highest priority science in ground-based optical/infrared and radio astronomy to be carried out by the Chilean community in the next decade with a preliminary look beyond that. The charge should call for identification of candidate lead instruments, including data facilities, which will address the highest science priorities for the next decade. It should call for a program that is transformative of Chilean astronomy and that would motivate the Chilean Government to support the transformation. The call should identify a target range of possible funding over the decade for realization of the program. This survey should take one year but may take longer due to the care with which it must be explained and chartered. It should include a process to incorporate input from the international observatories and broader communities (faculty professors, scientists, postdocs, engineers and graduate students. It should recognize that this process will likely result in a level of strategic focus in Chilean astronomy and that agreeing on any increased level of focus and which focus to embrace may require significant discourse.

We argue that Chile must develop its own indigenous astro-engineering thrust and that it must invest in Chilean astronomy as a first step to leveraging the presence of the majority of global astronomy in Chile. This is a difficult task that will take resources and a commitment to a grass roots effort with the Chilean astronomy community. It will require the aforementioned development of a strategic decadal plan for Chilean astronomy with the community and the diligence to carry that plan out over an extended time. It will likely require recruiting key talent into Chile. It will require enthusiastic public support.

The course that we recommend mirrors the approach taken in several emerging Asian economies and differs from more incremental examples followed in absorbing new economies in the European Community. In order to leverage strong positions in trade and growing positions in Singapore, Hong Kong, Taiwan and mainland China, leaders have made rapid significant investments in infrastructure, importing, recruiting and re-immigrating leadership human capital, adopting best practice institutional models and establishing world class capabilities in a single generation. As a result, research and education institutions in these locations are playing leadership roles in many areas, competing head to head for investment and attracting star talent on the world market. This differs significantly with models followed in, for example, emerging second tier European countries that advance by collaborating with leadership institutions in Germany, France, Switzerland, etc. such as the European Organization for Nuclear Research (CERN) and the European Southern Observatory (ESO). The latter approach is positive and slow and steady. Leadership, however, remains in its original settings. With Chile's global astronomy asset and its existing embryonic astro-engineering groups, the Asian model presents an opportunity for Chile to work in a single generation to join the front ranks of this seminal technology.

We propose that Chile should sponsor one or two leading initiatives in astro-engineering with the aim to deliver a Chilean led instrument for use by the Chilean astronomy communities at observatories in Chile. We propose that one initiative be carried out in optical/infrared astronomy and one in radio astronomy. These initiatives should deliver a significant Chilean led camera, spectrograph or other observing instrument, or a significant data processing and analysis facility that provides equivalent scientific impact to the community.

We propose that this initiative not be a mere lateral or subordinate collaboration with the international observatories, though such an "apprenticeship" might be viewed as a logical progression. **We propose that Chile seek a leading role. Chile's astronomy skies lead the world. Chilean indigenous astronomy and its spinoffs should lead as well.**

We predict that each of the two initiatives would require significant investment with funds in the USD5 million to USD20 million range for each, spread over 5 to 10 years.

Existing and new international observatories in Chile develop, install and operate significant new instrumentation in order to remain competitive and to react to the emerging frontier questions in science. These instrumentation efforts are a steady and significant part of each observatory's program. Numerous opportunities exist. As the Chilean astronomy community receives 10% of the observing time on most of the international observatories, we propose that Chile's proprietary interest in that observing time be viewed as equity to motivate the development and use of Chilean astronomy instrumentation at one or more of the international observatories. Chile should seek to lead in providing 10% of the instrumentation. The international observatories need not be asked to provide additional observing time for the use of these instruments by Chilean astronomers, but may negotiate to use these with their own time. To leverage Chile's observing time to lead to accommodation of Chilean instruments by the observatories, the initiatives would have to compete in the international peer review process that is in place. The initiative we propose should be prepared to earn its place in the meritocracy.

This Roadmap contains other significant recommendations, as well. In our main advice, we propose an initiative to start the more complete exploitation of Chile's remarkable skies and the extraordinary international observatories established under those skies. These first steps do not require immediate active partnership with industry nor with the observatories though such partnership is not excluded and can be developed in parallel. What is required is earnest involvement of the government agencies and the Chilean astronomy community. **Persistence is also required for a process that will take one to two years to launch and a decade to bring to delivery.** Success will deliver the instrumentation for a first rank Chilean astronomy thrust and a world class Chilean astro-engineering capability able to catalyze innovation beyond astronomy.

1 Background

In May 2011 the National Commission for Scientific and Technological Research (CONICYT) formed a working group charged to evaluate current capabilities in Chilean industry and universities related to producing technology with applications in astronomy, and to provide recommendations to boost such activity in Chile.

This work is motivated by the following:

- That Chile enjoys superb atmospheric conditions that facilitate research in astronomy at all wavelengths.

- That Chilean Governments have reliably and continuously supported the discipline of astronomy for more than 150 years.

- That a legal framework, sponsored and supported by the Chilean Government, is in place that has successfully allowed some of the leading international research organizations to become established in Chile for the development and operation of astronomical observatories.

- That the Chilean Government has sponsored environmental norms intended to preserve the photometric quality of the night sky in the regions where astronomy research is taking place.

- That Chilean universities have successfully developed astronomy programs to pursue research as well as education at undergraduate and graduate level. Furthermore, these universities have managed to develop their own collaboration agreements with international universities that host some of the best astronomy programs in Asia, Europe, USA, Canada and Latin America.

- That the number of professors, postdocs and graduate students in astronomy has significantly increased over the last 15 years, representing about 2% of the domestic scientific community in Chile.

- That university groups have moved forward, with fiscal funding, the specific funding for Astronomy such as the GEMINI-CONICYT, ALMA-CONICYT and the Joint ESO-Government of Chile funds, and in some cases their own funding, creating conditions for the establishment of highly specialized technical groups for: i) the development of astronomical instrumentation, with some important progress already achieved in areas such as prototyping microwave receivers and construction of optical spectrometers, ii) formation of research groups and development of tools for the accurate forecasting of turbulence and water vapor over astronomical sites, iii) conceptual development and prototyping of instruments for accurate monitoring of atmospheric conditions at observatory sites, as well as iv) development of complex computer codes to support astronomical operations and data analysis at leading observatories in Chile.

For completeness, a chronology of astronomy developments in Chile is summarized in Appendix A of this document. The chronology begins with the first scientific missions arriving in Chile in mid XIX and early XX century, bringing with them astronomical instrumentation that helped initiate observational astronomy in our country. Appendix B summarizes the historical development of astronomy in Chile, including: details of the beginning of astrophysics, the development of undergraduate and graduate astronomy programs at the Chilean universities, and the important establishment of international observatories and major telescopes in the northern regions of the country.

2 The members of the working group

Dr. Mónica Rubio, Program of Astronomy at CONICYT
Dr. Gary Sanders, Thirty Meter Telescope
Dr. Angel Otárola, Thirty Meter Telescope
Ms. Friederike Toepfer, Department of Studies and Strategic Planning at CONICYT
Ms. Gloria Maldonado, InnovaChile, CORFO, Ministry of Economy
Mr. Víctor González, InnovaChile, CORFO, Ministry of Economy
Mr. Andrés Barriga, Innovation Division, Ministry of Economy
Mr. Guillermo Acuña, Innovation Division, Ministry of Economy
Ms. Karen Molina, Directorate of Energy, Science, Technology and Innovation (DECITY), Ministry of Foreign Affairs
Mr. Cristián González, National Innovation Council for Competitiveness (CNIC)

With the collaboration of: Ms. Andrea Zúñiga Cabrera, Ms. Paola Jarpa Riquelme, Mr. Patricio Vásquez and Ms. Camila Serra, all from CONICYT.

This working group benefits largely from the experience of Dr. Gary Sanders in the development and management of some of the largest and highest impact infrastructure projects in science such as: the Laser Interferometer Gravitational Wave Observatory (LIGO), and the Thirty Meter Telescope (TMT) Project; from his research at Princeton University, Los Alamos National Laboratory, and the California Institute of Technology; as Principal Investigator of Project Science: Education and Training in the Management of Big Science Projects, a workshop series supported by the US National Science Foundation since 2001; long experience acquired through participation in numerous committees overseeing the design, implementation and operation of science projects.

During 2012, Juan Manuel Santa Cruz and Felipe Torres from the Innovation Division of the Ministry of Economy, Francisco Martínez from Corfo/Innova, joined the working group replacing Andrés Barriga, Guillermo Acuña and Víctor González, respectively, whom had left their organizations.

3 Methodology

The working group conducted two face-to-face meetings in May and November 2011, respectively. In addition, a series of videoconferences (13 in total) were used by the working group to devise strategies to fulfill their goals, to create the means to gather information and to meet with the stakeholders to receive their input.

4 Stakeholders

Astronomy activity in Chile involves active participation of many actors: the Chilean Government and its several ministries and public offices that are concerned with astronomy activity including the Ministries of Foreign Affairs, National Assets, Economy-Development & Tourism, Education, the National Service for Tourism, Regional Government in those regions hosting astronomical observatories, and most important, the observatories and Chilean universities. Chilean industry also plays an important role as a provider of goods and services to the observatories. Several industrial associations are interested in identifying market opportunities for the participation of their affiliates.

Representatives of the stakeholders were interviewed in order to understand current astronomy related technology capabilities in Chile. In particular, interviews were conducted with those participating in astronomy research and technology development in university settings, industrial associations to learn the current involvement of local industry in astronomy projects in Chile, as well as international observatories established in Chile with the goal to learn about their plans for future upgrades, instruments development and their interest to partner with local companies, and/or university groups, for the development of technology and integration of technologies in future upgrades at their facilities.

The task of interviewing the major stakeholders was only partially successful, with constructive responses from the various researchers and engineers working in astronomy at Chilean universities and a few of the international observatories. Questionnaires were sent by the Innovation Division of the Ministry of Economy to ten representatives and directors of observatories in Chile, but only two observatories responded to the survey and participated in additional interviews (Appendix E provides a complete list of observatories which received the survey and those which responded). As it will be clear from our recommendations below, information from all observatories could help clarify the best way to channel our recommendations.

The working group also agreed to hire a consultant to survey local industry actors and the engineering groups at the international observatories to learn the following: i) the interest and readiness of local industry to develop technology (or integrate technologies) for astronomical observatories in Chile, ii) the observatories' plans for technology upgrades and instrument development in the medium and long terms. This effort was undertaken by the Ministry of Economy. The conclusions of this consulting contract were delivered in May 2012. The additional material has been reviewed and is considered to be compatible with the status of the affairs as reported in the Roadmap. We can say succinctly that Chilean industry has been participating, through local direct contracts and/or in association with international companies, in the early stages of the construction of astronomical observatories in Chile. Their participation is mainly in areas related to: civil works, structural mechanical assembly, rental of specialized construction equipment, transportation of astronomical infrastructure (such as mirrors, telescope structural components, etc.), and as providers of goods and services for the daily operation of the observatories. Additionally, in recent times some Chilean companies have had the opportunity to participate in some critical contracts for the observatories such as installation and splicing of the specialized fiber optics needed for accurate and reliable transmission of astronomical signals from detectors to processing units, and in the integration of the backend technology needed for the processing of the signals detected at the radio telescopes of the Atacama Large Millimeter Array project. This has only been possible when procurement calls are open and Chilean industries could apply. More often, procurements calls are part of inkind contribution of the partners involved in the project. In summary, it is fair to say that Chilean industry, at this stage, is participating mainly in the construction stage of astronomical projects, with a few examples of participation in the integration of technologies consisting of electronic signal handling units that were already developed elsewhere by international partners of astronomical observatories.

5 Chilean Universities as developers of technology for astronomy

Among the most enthusiastic groups participating in the Roadmap survey were the researchers and developers at Chilean universities. To assess current capabilities, funding status, as well as immediate and future interest of these developers, a survey was submitted to each astronomy group. For reference, this survey is included in Appendix C.

Responding groups were invited to a follow up meeting with members of the Roadmap working group, either in person or via videoconference. These face-to-face meetings allowed the researchers more latitude to explain their future plans, and provided more opportunity to learn about their particular funding/manpower situations, readiness to engage in design and fabrication of complex astronomy instruments and to get their further suggestions. The following lists the university groups that responded to the survey and participated in this part of the study:

- Pontificia Universidad Católica de Chile, Center for Astro-Engineering
- Universidad de Chile, Cerro Calán National Observatory, Millimeter-Wave Laboratory
- Universidad de Chile, Department of Electrical Engineering
- Universidad de Concepción, Department of Electrical Engineering
- Universidad de Chile, Center for Mathematical Modeling
- Universidad de Concepción, Astronomy Department
- Universidad de Valparaíso, Centro de AstroMeteorología
- Universidad Técnica Federico Santa María
- Universidad Católica del Norte, Institute of Astronomy

From the information provided by each organization, it was encouraging to learn that, at any given time, there are more than 180 people among professorial faculty, postdocs, graduate students, undergraduate students, engineers, technicians and support staff participating in the development of technology (first generation spectrometers, radio astronomy receivers, cameras), technical studies with applications in existing observatories, and programming of computer code for telescope control. One of the groups has also developed physical and mathematical models to effectively compute and forecast meteorological variables and to help decide which astronomy programs best match the atmospheric conditions. This contributes to maximizing the scientific productivity of the observatories.

Appendix D summarizes the information collected from the universities through the survey and face-to-face meetings. This information provides a clear status of the major interests in developing technology at the various universities, the projects that are under development, the partnerships these groups have established with international centers and laboratories developing astronomy technology, and, most important, summarizes their views and recommendations to help boost the development of astronomy-technology in Chile.

6 Highlights of astronomy related technology development at Chilean Universities that participated in the Roadmap survey

Pontificia Universidad Católica de Chile: Development of a high spectral resolution echelle optical spectrograph at the Center for Astro-Engineering, Pontificia Universidad Católica de Chile. This is an indigenous instrument, designed and built with participation of a leading project scientist and with participation of local graduate students and engineers. The instrument, though of small scale, represents an interesting step towards the participation of this research group in the design and fabrication of larger instruments. This research center has already established collaboration links with institutes in Europe and in the USA for the design and construction of components needed in larger instruments proposed for the European- Extremely Large Telescope (E-ELT) and Giant Magellan Telescope (GMT) projects, and recently (motivated by the work of the Roadmap working group work) has managed an agreement for participation in instrument development for the Tokyo Atacama Telescope (TAO) project.

Universidad de Chile: Development of radio frequency Band 1 by the Millimeter-Wave Laboratory at Cerro Calán National Observatory, Universidad de Chile. This consists of an actual microwave receiver operating in one of the spectral bands of scientific interest for ALMA. In the development of this prototype receiver, Chilean researchers and scientists have already established strong ties and collaboration with advanced instrument development centers in Europe, North America and Japan. Importantly, they have successfully completed a prototype receiver with the help of internal funds from the university and public funds available through specific programs operated through CONICYT, and from European competitive funds obtained through partnership with international laboratories (i.e. FP6). On the other hand, the Department of Engineering has been developing interesting areas of technology such as photonics and terahertz radio frequency receivers, and has been engaged in the design and fabrication of a CubeSat with sensors to study ionospheric physics. The terahertz technology could easily find applications in medicine, pharmacy and homeland security through the development of specialized imaging and spectrograph systems.

Universidad de Concepción: Development of digital-backend profiling radiometers to monitor the amount of water vapor in the atmospheric column at observatory sites. This is taking place with participation of both the Astronomy and Engineering groups. Instruments like this can be used in multiple disciplines, not only in astronomy. Accurate measurements of atmospheric humidity are important in climate studies and are useful in the field of numerical weather forecasting. Because some astronomy spectral bands are sensitive to absorption by atmospheric water vapor, these kinds of radiometers are used in studies intended to identify suitable places for the establishment of radio and millimeter wavelength observatories. Recently, this group has also established links with the Haystack Observatory (MIT), to participate in an NSF[1] Major Research Initiative, consisting of adding a VLBI Backend to the ALMA observatory and allowing integration in a worldwide very long-baseline interferometer. This effort intends to achieve an angular resolution able to map the surrounding physical conditions of very compact objects, such as the Black Hole in the center of our galaxy (Milky Way). In the field of mathematical algorithms, they have successfully developed algorithms for the transmission of high volumes of data over Ethernet links; work like this has applications beyond astronomy to general data centers and to streaming of movies, music, etc.

Universidad de Valparaíso: Development of an Astro-Meteorology group. The Center for Astrophysics has supported the establishment of a computer cluster and a group of experts in numerical weather predictions and techniques for the monitoring of atmospheric turbulence and water vapor. This group applies meteorology techniques, in macro and micro scales, for the prediction of atmospheric conditions at observatory sites to support their operations and the scheduling of their observation programs. This helps schedule the observations with the best matched atmospheric conditions, which increases the scientific output of the observatories. The prediction products can also be used in other areas of the economy i.e. agriculture, or defense, that require closely following the atmospheric conditions with fine time and spatial resolutions.

Universidad Técnica Federico Santa María: Specialized software and computational algorithms. This work takes place at the Computer Systems Research Group which has been involved in the development of computational architectures for ALMA Common Software (ACS). They have also been involved in successful development of a telescope task scheduler to handle the astronomy projects and to automate the high-level commands that steer the telescopes to astronomy sources and start the data acquisition in a dynamic scheduling framework. In a dynamic scheduling environment, the astronomy programs are matched to the scientific requirements and to available resources (technical and atmospheric) maximizing the use of resources and, ultimately, the scientific output. This research group is involved, mostly with the ALMA Observatory, in several other studies that do require the participation of highly specialized computer systems and algorithms.

Universidad Católica del Norte: Institute of Astronomy. This group is not reporting development of technology at this time. They have reported ongoing scientific research in the areas of X-ray spectroscopy, imaging of Active Galactic Nuclei (AGN) and optical spectroscopy of early type stars and of the interstellar medium. Their students have been participating in site testing activities carried out by the European Southern Observatory for the European Extremely Large Telescope (E-ELT) project and one of their students was Student Researcher resident invited by the California Institute of Technology (Caltech) to work on the analysis of atmospheric turbulence data gathered by the Thirty Meter Telescope (TMT) project during their site testing campaign in Chile and elsewhere. This university group is located right in one of the fastest developing regions for astronomy projects (such as VLT, ALMA, E-ELT and other projects located in the area of Llano de Chajnantor), and is poised, with some visionary restructuring of their main objectives, to go beyond current science activities, to exploit their access to some of the best observatories in the world.

[1] USA National Science Foundation (NSF)

Collaborative efforts: Based on the answers to the survey from the various university groups (Universidad de Chile, Universidad de Concepción, Pontificia Universidad Católica de Chile) it is easy to identify areas of common interest with high potential to increase synergies. Specifically, in areas such as design and development of passive remote sensing microwave systems for the monitoring of atmospheric water vapor and the development of the retrieval algorithms necessary to convert the fundamental measurements to the magnitude of the physical variable of interest (either atmospheric temperature, moisture or turbulence). In addition, in the area of photonics, efforts are taking place at the engineering departments at Universidad de Chile and Universidad de los Andes, where lasers can be applied not only to astronomy but to applications in communication and remote sensing of the atmosphere.

Another important collaboration taking place in Chile is that giving form to the National Laboratory of High-Performance Computing (NLHPC), hosted at the Center for Mathematical Modeling (CMM, Universidad de Chile), with participation of Red Universitaria Nacional (REUNA), and Pontificia Universidad Católica de Chile, Universidad de Santiago de Chile, Universidad Técnica Federico Santa María, Universidad de Talca, Universidad de La Frontera (UFRO), and Universidad Católica del Norte. This laboratory has been initiated recently with funds from the Programa de Investigación Asociativa (PIA) of CONICYT at the level of USD 3.5 million. CMM and NLHPC have the potential to play an important role in the managing, processing and mathematical/digital analysis of astronomical data originating from the observations of the Large Synoptic Survey Telescope (LSST) to be installed in the Region of Coquimbo. LSST, a US project with important funding from NSF (USD 500 million), includes a 3.2 GBytes astronomical camera that will cover a large field of view and will be able to map the whole sky once and again every three days for a period of ten years. Clever analysis of whole sky images will allow scientist to learn the effects of dark matter, dark energy and weak lensing. The volume of information generated every night is unprecedented (30TBytes per night), and the fast-whole-sky imaging capability of LSST will allow detecting hundreds, if not thousands, of transient events per night including supernovae, new variable stars, asteroids, comets, etc. that need to be detected timely and communicated to the scientific community. CMM and the NLHPC have the infrastructure and the expertise to participate in providing computing power and intelligence for the analysis of LSST data.

7 International observatories in Chile as an opportunity for using technology developed by Chileans

Chile hosts an important fraction of the international astronomy research centers funded by European, USA and Japanese resources. These international observatories have been established in Chile since the early 1960s. A historical account of the development of astronomy in Chile is provided in Appendix B, and an updated list of the existing international astronomical observatories already established in Chile is made available in Appendix F. The magnitude of capital investment of some of the existing and planned astronomical observatories is listed in Appendix G. The most recent large astronomy project established in Chile is the Atacama Large Millimeter Array (ALMA) in the Cerro Chajnantor in the Region of Antofagasta in northern Chile. In addition to this important project there are plans to deploy three of the largest optical and infrared large-aperture telescopes currently under design and development; the Large Synoptic Survey Telescope (LSST), the European Extremely Large Telescope (E-ELT), and the Giant Magellan Telescope (GMT). There is no doubt to this working group that these projects should provide an opportunity to foster collaborations with Chilean astro-engineering centers for the development of some of the astronomical instrumentation and/or support technologies that are needed in the development of these large telescopes.

7.1 Parque Astronómico de Atacama

A major initiative undertaken by CONICYT in Chile has been the development of the Parque Astronómico de Atacama, a scientific reserve protected for astronomy. The idea originated in about 2002 with the goal to secure the land surrounding the ALMA project for other astronomical projects interested in deploying in Chile, which had been declared a scientific reserve in 1998. This Parque Astronómico is an ideal solution for small and medium size astronomical projects (under USD 300 Million), operated by national or international university consortiums to gain access to some of the best conditions for astronomy research in the world. The following are a few examples of the astronomical projects already operating or expected to be deployed within the boundaries of the Parque Astronómico de Atacama:

The Atacama Cosmology Telescope (ACT) Group: This project consists of a 6m-diameter radio-telescope designed and built to study the cosmic microwave radiation; this is the relic radiation from the decoupling time and bears the signature of the primordial processes that gave shape to the universe as we know it today. Detecting and studying this microwave radiation helps the scientist understand how our universe formed evolved and hypothesize about its fate. This project has been developed with the participation of important universities with leading efforts at Princeton University and University of Pennsylvania in the USA and funds from the US National Science Foundation. In Chile, ACT collaborates with the Pontificia Universidad Católica de Chile. In the few years that ACT has been observing from the site that is now part of the Parque Astronómico de Atacama, this telescope has performed important discoveries such as the detection of the kinematic Sunyaev-Zel'dowich effect, a physical effect proposed in 1972 by Russian scientists. The successful detection of this effect provides the scientist with a tool to measure the velocity of galaxy clusters at larger distances than current methods allow and understand the physics of the universe at very large spatial scales.

The Tokyo Atacama Observatory (TAO): This is a project of University of Tokyo which plans to operate a 6.5m telescope at the highest point of Cerro Chajnantor in the Region of Antofagasta. Because of its geographic location and altitude, TAO will observe the cosmos through a very dry atmosphere. The high altitude and dry atmospheric conditions will open new scientific spectral bands in the mid-infrared, which until now have only been exploited from telescopes orbiting the planet. At present, the group is operating a 1m experimental telescope, the mini-TAO telescope, at 5640m of altitude and has confirmed the excellence of the site. The scientist leading this research group (Dr. Mamoru Doi) has expressed his interest in establishing collaborative efforts with local instrumentation developers at Chilean university centers, and as this report is being written we understand an agreement is being discussed for the development of astronomical instrumentation with the center of astro-engineering at the Pontificia Universidad Católica de Chile.

The CCAT Project: This project has participation from several university groups under the leadership of Cornell University and California Institute of Technology (Caltech). The project consists of a 25m-diameter radio-telescope of a very high sensitivity, wide field of view and is driven by very important scientific goals. CCAT, in many aspects, will be complementary to ALMA and will provide unique information in the study of the gas around the cluster of galaxies and proto-planetary disks at very early stage of formation.

Several other university projects are being installed, i.e. PolarBear from U. Berkeley and CLASS from Hopkins University. Projects such as TAO, ACT and CCAT represent a great opportunity to the developers of astronomy technology in Chile to partner and participate in the instrumentation needed for those telescopes to purse their science goals as these are still in their definition and design phases (see section 8). The Tokyo Atacama Observatory group, ACT and the Chajnantor Test Facility of the California Institute of Technology answered the questionnaire submitted by the

Roadmap Working Group to the observatories (see Appendix E). In summary, it is highly advisable for Chile to foster and strengthen links between the international observatories already operating or being established in Chile in the near future and their Chilean counterparts for making further progress in projects such as the examples included here.

8 Fostering astro-engineering in Chile

8.1 The astronomy technical process

Astro-engineering is the process by which the needed observational capabilities are delivered to the astronomer so that the science can be carried out. It begins with science goals and results in the observational capabilities embodied in telescopes or radio receivers (for ground-based optical/infrared and radio astronomy as practiced in Chile), in the cameras and spectroscopes and other specialized science instruments mounted on the telescopes or receivers, and in the data collection, archiving and processing tools, hardware and software, needed to yield scientific data suitable for interpretation. The sum total of these constitutes an observatory.

The path to the finished observatory or its component instruments and software starts by identifying the science goals. For each science goal, the astronomer determines the observational requirements that will be needed, such as the amount of light to be collected, the time period over which the observation is to be made, the wavelength range of the light or radio waves to be collected, the needed resolution in measuring a light spectrum or the needed image sharpness. The list of required capabilities to carry out a specific science goal may be long. This list is called the science requirements. In order for an engineer to design and deliver an observatory that meets the science requirements, the engineer must work with the astronomer to translate the science requirements to a set of technical requirements that can be used by an engineering team to develop a design concept for the observatory. This concept illustrates how the technical requirements may be met. With the design concept established, research and development (R&D) and further design leads to a design that is not illustrative, but is a definitive choice among design alternatives. This is called the preliminary design. This design is then detailed to produce documentation to control fabrication and construction. This final design enables construction, integration and commissioning of the observatory. Science observations follow.

This sequence of steps is the system engineering of astronomy. Given the frontier scientific goals of the astronomy practiced in Chile, technology is pushed to the limit in scale, precision, stability, reliability and in the use of entirely new technologies. The process carried out by the astro-engineers and their astronomer colleagues constitute a very specialized expertise that ranks with the work done by the most demanding efforts in technology.

8.2 The astro-engineering setting and community

A few hundred to a few thousand specialists constitute the global ground-based astro-engineering community. Within Chile, native Chileans constitute a small fraction of the global community, especially if one focuses on those experts who can initiate and lead large scale astro-engineering projects. Most Chileans who work in astro-engineering are on the staff of observatories playing contributing roles. A key attribute of experienced leading astro-engineers are that they are plugged into global high-technology industries. Astro-engineering projects are "one-of-a-kind" projects that involve leading edge technology. Invariably, industrial design and fabrication are needed and only the most sophisticated specialty optics, detector, aerospace and precision engineering firms are matched to this challenge. The projects are sophisticated and industry partners are among the elite firms in the world.

The astronomers and their astro-engineer teammates are almost always in a university or observatory academic setting, though we will discuss the more industrial model that ESO exemplifies. Even for ESO, the astro-engineers often originate in or are adapted to their academic community. The stakeholders who want the products of astro-engineering are also academics. They set goals and engage during the project experience, communicating their needs and culture. This results in specialized "boutique" teams functioning globally in an extended community. For Chilean astronomy and astro-engineering to advance to the next level, and to seed innovation that can percolate beyond astronomy in Chile, creating leading boutique teams based in Chile is an early step that Chile can take unilaterally.

No matter how unilateral an initiative is, the products of Chilean astro-engineering must be delivered to the international observatories in Chile. A Chilean team, leading an astro-engineering project, must collaborate with the observatory to which the product will be delivered for use. At the very least, the observatory must rank the science goals high and conclude a favorable and competitive peer review of the Chilean team and their plans. Collaboration may be deeper including teaming in design and all other phases of the project. However, we are not considering collaborations where the leading effort is at the international level and the Chilean team participates only as a fractional contributor. This would not seed the kind of innovative capability that should be a Chilean goal.

8.3 Hollywood as a template for astro-engineering

As we shall see, the international observatory communities in Chile possess similar expertise, but generally approach the organization of their work in three distinct ways. These differences reflect culture and funding agency practices. For two of these, the two different organizational eras in making Hollywood movies provide a good template.

8.3.1 Hollywood studio system and the ESO model

Seventy five years ago, Hollywood movies were produced by very large studios such as MGM. These large firms had leading actors under exclusive contract, operated significant capital assets such as sound stages, large prop departments, and costume shops. Nearly every skill or infrastructure needed to deliver movies to the theater screen was available continuously under one umbrella. This enabled serial production of routine movies with great cost efficiency, as well as the blockbuster or historically great films whose economic risk rode on the diverse portfolio of lesser works. The studios could develop their staffs, their skill sets and capabilities. They could make almost routine what was a "one-of-kind" activity. Despite the economic efficiency in serial production, this business model was costly. It functioned well when movies dominated the entertainment market, riding on expansion.

The European Southern Observatory (ESO) began its existence by adopting the model of the European Organization for Nuclear Research (CERN). CERN is an international treaty organization that has developed all capabilities for major projects in nuclear and high-energy physics, from the small accelerators of the 1950's to today's Large Hadron Collider, the single largest completed ground-based scientific project in history. ESO adopted the CERN model in its early years when it was co-located in Geneva with CERN. It carried this model to its new headquarters near Munich, and to its facilities in Chile. The CERN and ESO models mimic the Hollywood studio model in many ways. ESO continuously employs a large and talented, even unprecedented, team of astronomers and astro-engineers. It also has all needed technical, physical and administrative infrastructure. These are supported continuously through treaty member annual subscriptions based upon member Gross Domestic Products (GDP). The funding stream is so stable that this astronomy "studio" can be maintained and even grown into new areas such as radio astronomy with the ALMA project. It is large enough that new capital projects can be funded generally within the base funding stream with more modest "investment" funding riding on the base. While ESO engages a large industry supplier base and supports collaborating European university groups with coordination and some capital funding, ESO is the strong nucleus around which new astronomy opportunities are realized. Like the

Hollywood studio model, ESO and CERN provide a maintained and developed collection of powerful capabilities well suited to an expansionist European economy and social model. Both institutions are surviving well, for the moment, even in the current more challenging European environment.

8.3.2 Hollywood single productions and the US astronomy model

More recently, the business model for theatrical feature-length Hollywood movies has changed to an opportunistic single project model. Studios maintain only skeleton staffs sufficient to review, approve, manage, advertise and distribute movie projects. Persistent contract talent is the exception. When a movie enters production, a project team is assembled. Financial sponsors (producers), project managers (directors), lead talent (stars) and all of the talent, artistic, musical, technical, and logistic skills are assembled in a one-time-only production team. A production is a discrete project. Even physical assets such as costumes, props, camera equipment, and sound stages are located and rented for the period of the production. An ecology of firms provides the environment for projects of limited duration, and replicates the former capabilities of the studios. Each participant in the ecology, or cluster, is responsible for its own quality and economic efficiency. In this model, surges or ebbs in demand are accommodated by layoffs, contract closeouts, and geographic mobility and even by mergers, acquisitions, failures and startups of film production firms at the top of the ecology food chain. This model is built in small units around specific talents and expertise (actors, cinematographers, artists, musicians, etc.). The units function as small entities of creativity and service. For each film, a fully capable project team is created, managed and dismantled. This is a very different model from the steady-state team of early Hollywood. It is responsive to the market where movies occupy a smaller fraction of the total entertainment share, to the smaller number of more expensive and risky productions and to tenacious pressure for economic efficiency in an era of diminished opportunities for expansion.

This is the model that best represents American science projects, in general, and American astronomy projects in particular. Though it is an adaptation to a shrinking market, this model of American astro-engineering has its roots in the preeminent position of academic scientists in American science culture facilitated by the economics of US support for science. In fact, American large scale physical science began to follow a route similar to CERN and ESO, but it ultimately took a different path.

In the same post World War II economic expansion and optimism that led to CERN, the US established large national laboratories. Flush with the success of the large Manhattan Project laboratories, the first 25 post-war years saw national laboratories (Brookhaven, Stanford Linear Accelerator Center, Argonne, Fermilab, and smaller nuclear physics facilities). The early years of these laboratories yielded the same kind of stable ensemble teams and infrastructure that was assembled at CERN, and emulated by ESO. But the individualism in US culture, and the preeminent role of the university scientists, caused each of these laboratories to organize their programs to serve their academic clients. While the Europeans serve a similar clientele, in time the US laboratories grew an increasingly service culture and scientific projects were often led by academics outside these laboratories.

In US astronomy, the preeminence of the academics was more evident. When the post-war expansion of publicly funded science led to a national optical observatory (National Optical Astronomy Observatory (NOAO)) established in 1957 under the US National Science Foundation (NSF), the university astronomers, nourished by private funds raised by individual universities, resisted the full development of NOAO. NOAO was relegated to building telescopes that were a step behind the leading edge. A strong NOAO could not develop anything like the ESO model. While it grew in strength in many ways, several large NOAO initiatives met resistance.
Enabled by private funding, university astronomy groups that chose to develop technical (astro-

engineering) capabilities became the boutique teams that knew how to develop and deliver cutting edge astronomy instrumentation, and even cutting edge observatories. This model is the single project model described earlier. An instrument, or even an entire observatory (i.e. Keck Observatory in Hawaii, Las Campanas Observatory in Chile) are conceived of by a small group that ultimately attracts funding, builds a project team, executes the project and dismantles the elements of the team that are not needed to exploit the delivered product. The dismantling is often nearly complete, leaving behind only astronomers and those technical personnel needed to operate the instrumentation. Attempts to preserve core competencies as a resource for future projects have met with periodic success. More recently, however, capabilities that have been retained have been reduced or are under great pressure to divest capabilities and personnel that are not needed. American astro-engineering is largely a confederation of academic boutique groups who deliver sophisticated instrumentation by buildup of the team, execution of the project and substantial dismantling of the precious capabilities that were joined for the unique project.

American radio astronomy is slightly closer to the European model as the US National Radio Astronomy Observatory (NRAO) has built and operates the largest radio facilities (VLA, Green Bank, E-VLA, ALMA). American radio astronomy never developed a competing private funding base. Even here, many important radio arrays are operated by universities or ad hoc consortia with high focus on service observing for their sponsor communities.

8.4 Japan: Another case

Japanese astronomy, a third international presence in Chile, follows an entirely different model. Japanese astronomy reflects the strong academic culture of Japanese groups, and an emphasis on analytical and observational skills among Japanese astronomers to the detriment of technical skills. Historically, Japanese physical science projects have been realized with very heavy industry presence. An extreme example is the 8.4 meter Subaru Observatory on Mauna Kea. This Japanese national observatory, though led by the National Astronomical Observatory of Japan (NAOJ), a government laboratory, was entirely designed, fabricated and installed on Mauna Kea by Mitsubishi Electric Company (MELCO). To this day, more than a decade after delivery of this turnkey observatory, MELCO still provides crucial operating and maintenance support to what is largely a proprietary product. This pattern reflects the weak technical abilities of Japanese astronomers and their institutional settings (there are generally no engineers or technicians in Japanese groups, for example) and the very strong political and social role that industry giants like Mitsubishi, Canon, Nikon, Ohara and others have come to play. While recent smaller observatories from Japan have been realized by strong groups from University of Tokyo and others, and NAOJ maintains an advanced development group, independent boutique groups are a minor fraction of Japanese astronomy with the industry-client model dominant.

9 Fostering astro-engineering in Chile

Chile can seek to leverage its many international observatories to strengthen general education, or science, technology, engineering and mathematics (STEM) education. Chile may act to stimulate Chilean astronomy itself. Industrial development can occur through captured innovation, elevation of skills and engineering challenges within Chilean industry and expansion of the service industries supporting the observatories. New and planned international observatories in Chile require significant new advanced science instrumentation.

We argue that the creation of one or two Chilean initiatives to lead the development, delivery and use of world-class science instrumentation in these observatories has the potential to significantly boost indigenous development of technology in Chile. In addition to other initiatives that may involve education, commercial stimuli, or creation of high technology industrial capabilities, we advocate that a key step in leveraging Chile's position is accomplished by staying close to the observatories' program needs and **positioning the Chilean astronomy community to lead in meeting some of those needs.** By this we mean understanding the scientific and technical needs of the observatories and the communities who use it (including the Chilean community that has 10% of the telescope time) and delivering instrumentation lead by Chilean groups. Chile can provide the support to attract, develop and establish one or more leading astro-engineering groups. These groups can then propose and succeed in peer-reviewed competition to develop and deliver instrumentation. This can lift the Chilean astronomy community onto the world stage of astronomy engineering (astro-engineering) and innovation, and bring the Chilean astronomy community to the next level. It will be the first piece of any industrial ecology that seeks to leverage astronomy in Chile. A stimulus to Chilean astronomy does not require immediate partnering with the international observatories or the industrial sector at the start but all efforts to strengthen links among these actors is obviously a must and should be encouraged.

As a frontier basic science, astronomy employs advanced mathematical, analytical and technical methods. The instrumentation of astronomy requires optics performing at the nanometer level, precision guiding, advanced multiple-input, multiple-output controls systems, comprehensive spectroscopy, imaging, interferometry and array phasing at all wavelengths, precision opto-mechanics, cryo-cooling, facility-scale software environments and systems, and large-scale distributed system integration. These techniques, methods and technologies underpin astronomy, can be used for example in mining activities, but they are also crucial to assuring the national defense. Furthermore, the scientific and technical workforces needed to design, deploy and exploit these technologies and methods are prerequisite to realizing these technologies within Chile. Leveraging the presence of international astronomy in Chile creates university, industrial and human capital assets of great advantage to the Chilean defense sector, as in OECD countries. Similarly, the defense sector in Chile may possess advantageous capabilities for astronomy in Chile as they may have experience in program and project management skills, or specific technologies, or industrial liaison that is of benefit Chilean astro-engineering.

10 Specific steps on the Roadmap for the Fostering of Development of Technology in the Field of Astronomy in Chile

In order to promote the further development of astro-engineering in Chile, and boost the development of technology in the field of astronomy, with potential impact in other sectors of the economy in Chile, a Roadmap is proposed along the following lines:

10.1 Increasing or creating new funding opportunities at levels higher than existing funding programs

Since early 1990s the funding opportunities for astronomy in Chile have shown significant progress. Programs such as GEMINI-CONICYT Fund, ALMA-CONICYT Fund, Programa Milenio (MIDEPLAN), Fondap, Anillos and Basal from CONICYT, have contributed in the order of USD 26 million in the last six years (see Appendix H for a summary of the funds and funding levels awarded to astronomy).
Despite the rise of opportunity and funding, the scale of Chilean astronomy is undoubtedly that of small science. Chilean expansion has fostered new small groups at more universities. The expansion has been supported by funding that is of small scale compared to what instrumentation development requires, but sufficient to start a new group up with modest infrastructure, instruments and little steady-state technical support. The new groups are able to develop observational abilities matched to some of the available viewing time. Small instrumentation or prototyping projects have appeared in a few settings. Some specialized expertise in computing and astronomical weather studies has developed. These are significant positive developments; however, they are not of sufficient scale to lift any element of the Chilean community to major or leading roles in astronomy projects that require big science methods and significant astro-engineering.

Academic small science thrives on individual curiosity and initiative, private and opaque research team processes, invention and perfection by the scientists themselves and by peer-review publication of results as the recognized measure of science and success. Small science projects can take longer to realize, cost more than planned or even fail with little notice outside a local community. Any technical or engineering staffs in these small science groups are considered support workers, not elements of a flat and broadly skilled team.

Big science methods, needed to realize contemporary astronomy instrumentation and observatories that require tens to hundreds of millions of dollars, are essential to manage risks and to assure economic efficiency and delivery of the intended product. This is another kind of achievement. Big science requires successes both in the project's delivery of the observing system, followed by scientific success in peer-reviewed publication. Big science requires greater planning and scrutiny leading to open and transparent processes. It is a multidisciplinary activity in which the technicians, engineers and management specialists are every bit as important as the scientists for both types of success.

True multidisciplinary teams are needed to deliver modern astro-engineering. Such a flat multidisciplinary approach is an essential element of innovation. For Chilean astronomy to innovate, it must implement this model in, at least, a few key settings in Chile. Multidisciplinary groups are needed to assemble the balanced skill base for project delivery and for innovation that is exportable. It also creates a cultural readiness for teaming, essential to propagate innovation.

This committee has been impressed by the work accomplished already at the Chilean university centers. The current work that has been carried out with limited, though important, funding and mainly through the work of graduate and undergraduate students in Engineering and Astronomy, with the supervision of a senior project scientist/engineer. Increased funding is absolutely necessary to allow the university technology development centers to acquire capital equipment, hire of a healthy pool of engineers and technicians and hire postdocs specifically for participation in the design and development of instrumentation and, importantly, to allow participation in international conferences to keep up-to-date in current technologies and to stay in close contact with the activities carried out at their partner institutions abroad. Most important, an increment in funding significantly beyond current levels is needed to enable Chile to make a bold and visible step into Chilean-led world class astronomy instrumentation.

10.2 Conducting regular decadal astronomy surveys to gain a clear understanding of the interest and programmatic initiatives of the local community for the near, medium and long term in the field of astronomy

Some stimulus or incubation of existing small, but promising, Chilean astro-engineering groups may be part of this activity. We recommend surveying the possibilities as part of the process described below. Some early resources may be needed to begin this incubation and to draw the attention of groups towards this more organized activity.

It is essential that this initiative be firmly based on a science vision that is developed and embraced by the Chilean astronomy community. The very first significant step should be to commission a one-year long "decadal survey" of astronomy by the Chilean community. This study should call for a prioritized report of the highest priority science in ground-based optical/infrared and radio astronomy to be carried out and led by the Chilean community in the next decade with a preliminary look beyond that. The charge should call for identification of candidate lead instruments, including data facilities, which will address the science priorities. It should call for a program that transforms Chilean astronomy and that would motivate the Chilean Government to support the transformation. The call should identify a target range of possible funding over the decade for realization of the program. This survey should take one year but may take longer due to the care with which it must be explained and chartered. It should include a process to incorporate input from the international observatories and broader communities. It should recognize that this process will likely result in a level of strategic focus in Chilean astronomy.

In addition to the decadal survey, advice should be sought from external, non-advocate advisors representing astronomy, big science and innovation communities.

The decadal survey process should borrow from the recent US Astro2010 and European planning processes, or from the planning exercises carried out by smaller communities such as the Canadian Long Range Plan. A recent "Ground-based O/IR System Roadmap Committee Community Survey" carried out by the US NOAO was accomplished in 90 days and may provide a guide to first steps in a Chilean astronomy community process.

The process should include consideration of science opportunities with existing observatories in Chile (i.e second generation instrumentation), but pay significant attention to new observatories such as LSST, GMT, CCAT, TAO, etc. These new observatories represent forward looking science thrusts and may also be less hardened in planned instrumentation or, at least, more open to serious pro-active Chilean partnership. This consideration brings the demand from the observatories into the discourse within the Chilean astronomy community as they debate their highest priority science. We believe that this demand is significant.

Among existing observatories, Gemini South is part of a current Gemini community study of future instrumentation. This study may be completed before the Chilean decadal survey, which we advocate, is completed. Early communication with Gemini leadership may better align the timescales. ALMA is studying future RF band instrumentation. There may be opportunities at ESO's Paranal and Carnegie Observatory's Magellan telescopes.

For new observatory projects, we cite an example above with the TAO project and we suggest that the large projects E-ELT and GMT, though they have had instrument design programs with their current communities, are early in their development and serious consideration should be given to opportunities with these projects. Large observatories, such as E-ELT and GMT, require large mega-instruments as well as smaller scale instruments. At the smaller scales, the instruments are still quite challenging in realization and powerful in scientific reach. Possibilities may exist with CCAT. New opportunities may develop with new international communities seeking to enter into Chile with significant observatory investments. An example of this may be a new Chinese telescope in Chile.

To carry this out, three deficiencies in the current astronomy setting in Chile must be addressed (see section 9.4.1), and it must be recognized that we are advocating a "leap frog" initiative and not one that can build incrementally on an existing base.

Once a Chilean decadal survey is completed, with definition of one or two instrumental or data initiatives in the O/IR and radio disciplines, a call for proposals may be released inviting proposals for initiatives. Proposals should be reviewed by an expert committee that delivers recommendations to support the best one or two initiatives. This process could be a wide open competition or tied to recruitment of external recognized leadership into the Chilean community. Details should be worked out as the earlier processes evolve.

10.3 Fostering the development of indigenous astronomical instrumentation

We argue that Chile must develop its own indigenous astro-engineering thrust and that it must invest in Chilean astronomy as a first step to leveraging the presence of the majority of global astronomy in Chile. This is a difficult task that will take resources and a commitment to a grass roots effort with the Chilean astronomy community. It will require developing a strategic plan for Chilean astronomy with the community and the diligence to carry that plan out over an extended time. It will likely require recruiting key talent into Chile. It will require enthusiastic public support.

This should be possible. We have already noted that astronomy is part of the modern cultural tapestry of Chile. Careers in astronomy entail romance. Careers in astro-engineering must also be seen as part of the sparkle of starlight and the involvement of Chileans in cutting-edge technology. We propose that Chile should sponsor one or two leading initiatives in astro-engineering with the aim to deliver a Chilean led instrument for use by the Chilean astronomy communities at observatories in Chile. We propose that one initiative be carried out in optical/infrared astronomy and one in radio astronomy. These initiatives should deliver a significant Chilean led camera, spectroscope or other observing instrument, or a significant data processing and analysis facility that provides equivalent scientific impact to the community.

We propose that this initiative not be a mere lateral or subordinate collaboration with the international observatories, though such an "apprenticeship" might be viewed as a logical progression. We propose that Chile seek a leading role. Only through such a leading role can Chile truly maximize the impact of so much of global astronomy's assets in Chile.

We predict that each of the two initiatives would require significant investment with funds in the USD5 million to USD20 million range for each.

As the Chilean astronomy community receives 10% of the observing time on most of the international observatories, we propose that Chile's proprietary interest in that observing time be viewed as equity to motivate the development and use of Chilean astronomy instrumentation at one or more of the international observatories. These observatories need not be asked to provide additional observing time for the use of these instruments by Chilean astronomers, but may negotiate to use these with their own time. To leverage Chile's observing time to lead to accommodation of Chilean instruments by the observatories, the initiatives would have to compete in the international peer review process that is in place. The initiative we propose should be prepared to earn its place in the meritocracy.

Opportunities for this indigenous development of astronomical instrumentation can be done along the scientific spectral bands of the ALMA project, the coming CCAT project, in association with the opening of new spectral windows such as is the mid-infrared that is available for ground based observatories from dry sites in the western slopes of the Andes in the Region of Antofagasta. As a practical matter, some international collaboration should be expected. But we advocate a Chilean led effort aimed at exploiting Chile's existing equity in the observatories that it hosts.

10.4 Attract international expertise to Chile

Astro-engineering is the process by which the needed observational capabilities are delivered to the astronomer so that the science can be carried out. It begins with science goals and results in the observational capabilities embodied in telescopes or radio receivers (for ground-based optical/ infrared and radio astronomy as practiced in Chile), in the cameras and spectroscopes and other specialized science instruments mounted on the telescopes or receivers, and in the data collection, archiving and processing tools, hardware and software, needed to yield scientific data suitable for interpretation. The sum total of these constitutes an observatory.

A few hundred to a few thousand specialists constitute the global ground-based astro-engineering community. Within Chile, native Chileans constitute a small fraction of the global community, especially if one focuses on those experts who can initiate and lead large-scale astro-engineering projects. Most Chileans who work in astro-engineering are on the staff of the international observatories playing contributing roles. A key attribute of experienced leading astro-engineers is that they are plugged into global high-technology industries. Astro-engineering projects are "one-of-a-kind" projects that involve leading edge technology. Invariably, industrial design and fabrication are needed and only the most sophisticated specialty optics, detector, aerospace and precision engineering firms are matched to this challenge. The projects are sophisticated and industry partners are among the elite firms in the world.

In the world of astronomy, the development of a single complex astronomical instrument requires the participation of many actors. This includes, university groups (scientists, engineers, technicians), technology development centers (with the laboratory equipment and instrumentation required for the design, manufacturing, integration and test of the astronomical instruments), and also, importantly, industrial companies that provide key elements of the optics, mechanics, cryogenics, and electronics required for the specific astronomical instrument to get build. Typically, a special consortium is formed for the design, fabrication, assembly, testing and delivery of a given astronomical instrument. The instrument itself is unique and is specific for a particular telescope. It originates in the scientific goals that the community is supporting for that observatory. These consortiums are integrated by a combination of the actors mentioned above and stay together only for the time required to fabricate the highly specialized instrument. New consortiums are formed for the design and fabrication of other new instruments, and the actors who become involved are those who bring a particular expertise needed for the successful completion of the task at hand.

10.4.1 Qualified individuals with demonstrated track records in instrument development and management of medium/large scale astronomy projects

First, there may be no qualified and experienced scientists in the Chilean community with demonstrated readiness to lead and succeed in projects of the envisioned scale. This is a likely issue both in intrinsic ability to succeed in delivering the kind of projects that we advocate and in the ability to succeed in peer review at the outset by the community and the observatory that would host the instrumentation. We recommend that serious consideration be given to identifying internal candidates and involving them in the planning process, or, more likely, to searching for and recruiting a recognized international leader for each of the one or two initiatives advocated here. To leap Chilean astronomy forward may require importing talented leadership. Such recruitment should be coordinated with the decadal survey process described above. Indeed, that process may also be used to canvass and involve potential candidates. In particular, either as leaders, or significant participants, this process may also be used to attract overseas Chileans back to Chile, reversing any brain drain. This is similar to the policies followed by the Chinese science and technology agencies. Second, large project expertise may be absent in the Chilean science community as it is in many other national science communities. For complex one-of-a-kind astro-engineering projects, such expertise is needed though not of the scale that would be required for implementing an entire major observatory. This expertise can be coached into place by use of external reviewers and advisors and may well be assisted by some, but not all, of the observatories in Chile.

Third, the Chilean Government itself may not have experience in oversight of such large projects. It may be necessary for CONICYT, if they were to exercise oversight, to consult with counterpart agencies in other countries to establish appropriate oversight processes and expertise.

10.4.2 Attract and facilitate the installation of an International Center based upon known track record in the development of astronomical instrumentation

There are several well-respected technology development centers in the world. Perhaps, attracting one of those groups to get established in Chile and to work in close contact with the Chilean technology centers (right now working from within the local universities) is a model to be supported. A list of international technology development centers is provided in Appendix I. Some of the listed centers are already engaged in the development of instruments for astronomical observatories in Chile; furthermore, a few are already collaborators of Chilean universities for the design and development of components or whole instruments for large telescopes in Chile.

Should Chilean authorities support a model where an international center for the development of technology is attracted to Chile, to be effective for boosting the development of an indigenous program it is absolutely required that the international center collaborates with developers of technology in Chilean university groups and that the work is done with significant participation by Chilean scientists, engineers and technicians in all the phases of instrument development from design until final performance test and instrument delivery.

Sectors of the Chilean Government, including officers from the Directorate of Energy, Science, Technology and Innovation at the Ministry of Foreign Affairs (DECITY), Ministry of Economy and the National Commission for Scientific and Technological Research have participated in missions to Brazil to learn of their experience and capabilities in the development of major technology. In June 2012 an additional trip to Europe was organized by the Ministry of Foreign Affairs to meet with the industries that have participated in the development of technology for observatories such as ESO.

10.5 Foster the link between technology developers and relevant sectors of the economy and the national security

The technology of astronomical instrumentation (opto-mechanics, signal processing, digital imaging, adaptive optics, monitoring of environmental variables and accurate forecast of turbulence, clouds and atmospheric water vapor) as well as that of telescopes (precision micro-mechanics, high accuracy tracking systems, cryogenics, actuator controlled platforms, alignment & phasing systems) also has important applications in other sectors of the economy, industry and defense. To guarantee the development of technology in Chile it is highly advisable to generate bridges between the technology developers and these other sectors of the economy. In other words, Chile has to generate a policy to sustain in time the effort put towards developing its indigenous technology. In the US there is a wide experience from NASA, the Defense Department and the Energy Department in the generation of opportunities for local entrepreneurs to participate in confidential Request for Information calls to identify technical capabilities in small local companies and/or university groups to investigate the applicability of certain technologies, to perform mathematical and physical modeling to understand physical phenomena for their application in remote sensing, communications and national security, etc. In Brazil, EMBRAER is such an example and in Chile maybe ENAER, ASMAR and SISDEF could be mentioned. Also, there are regular funding opportunities to allow technical readiness in the use of technology with application in aspects of interest for these stakeholders. This maintains a group of talented engineers and scientists working and developing new ideas within university and small business research centers.

We further recommend the organization of an Industry Day 2012 as a way to communicate the results of the Roadmap to different stakeholders and to lay the foundation for further cooperation between government agencies, university groups, observatories and industry.

We have proposed an initiative to start the more complete exploitation of Chile's remarkable skies and the extraordinary international observatories established under those skies. These first steps do not depend upon immediate active partnership with industry nor with the observatories though such partnership is not excluded and can be developed in parallel. What is required is earnest involvement of the government agencies and the Chilean astronomy community. Persistence is also required for a process that will take one to two years to launch and a decade to bring to delivery. Success will deliver the instrumentation for a first rank Chilean astronomy thrust and a world class Chilean astro-engineering capability able to catalyze innovation beyond astronomy.

ASTRONOMY, TECHNOLOGY, INDUSTRY

Roadmap for the Fostering of Technology Development and Innovation in the Field of Astronomy in Chile

APPENDIXES DOCUMENT

APENDIX A

Chronology of Astronomy Development in Chile

1582: The first lunar eclipse is observed in Valdivia.

1849: A scientific mission from the Naval Observatory in Washington D.C. arrives in Chile with the intention to observe Venus and Mars and thereby calculate the distance between the earth and the sun. For this purpose Chile's first astronomic observatory is installed on Cerro Santa Lucia in Santiago. The mission ends in 1852.

1852: The instruments and observatory of Lt. Gillis are purchased by the Chilean Government to establish the National Astronomic Observatory (OAN).

1856: The National Astronomic Observatory moves to Quinta Normal district. By 1865, the observatory has achieved a reputation for quality research among fellow researchers in astronomy.

1868: Following Carlos Moesta as the director of the National Astronomic Observatory, José Ignacio Vergara establishes the Central Office of Meteorology in Chile and then starts to study the coordinates of Chilean cities.

1887: The National Astronomic Observatory participates in the production of the star catalogue – "carte du ciel" – organized by the International Astronomy Conference, using one of the seven identical Gautier telescopes around the world.

1903: A new mission from the Lick Observatory from California receives permission to build a telescope on Cerro San Cristobal, Santiago.

1917: On June 25, The Smithsonian "Solar Constant" Expedition sets up its camp in Calama, Chile. The expeditions started in 1917 in North Carolina but as this location turned out to be very cloudy, the expedition began to study climatic conditions in different parts of the world, such as the southern part of Africa, Argentina, and Chile. Climatic measurements indicate the Chilean desert to be the least cloudy region and of easy availability; the final location of the expedition is Calama on the Loa river banks at 2250m altitude. Here the number of cloudless mornings (at 7am), middays (at 2pm) and nights (at 9pm) reached 228, 206 and 299 respectively. Neither all cloudy days nor rain are registered during the expedition and temperatures vary between 0 and 25°C.

1927: The National Astronomy Observatory (OAN) becomes part of the Faculty of Physics and Mathematical Sciences at the Universidad de Chile, currently located on Cerro Calán, Santiago.

1929: Dr. Manual Foster, former student from the Pontificia Universidad Católica de Chile acquires the Californian Lick mission observatory and donates it to his former university. The telescope is located on Cerro San Cristóbal. Between 1975 and 1985 the researcher succeeds to extend his field of research to long-term photometric study of stars with varying brightness.

1959: The OAN is transferred from Lo Espejo to its current location on Cerro Calán.

1962: The construction of the Cerro Tololo International Observatory (CTIO) begins and ends five years later. The observatory is inaugurated in 1968.

1965: On April 25, ESO inaugurates the La Silla Observatory on northern part of Cerro Chinchado in Chile's Coquimbo Region. Due to its shape, the location is also known as Cerro La Silla.

1965: Universidad de Chile creates its Astronomy Department and starts a Bachelor Degree program (Licenciatura).

1971: The observatory at Cerro Las Campanas which belongs to the Carnegie Institution, takes up work with its first instrument, the so-called Swope Telescope.

1976: Universidad de Chile creates a Master Degree program.

1994: Ronald Mennickent, a recent doctorate of Phisycs at the Pontificia Universidad Católica de Chile, starts an astronomy group when hired by the Physics Department at Universidad de Concepción. Universidad de Concepción is currently the third most important university outside of Santiago.

1996: Following decree n° 26/96, Universidad Católica del Norte launches a new astronomy institute.

1998: In March of this year the Pontificia Universidad Católica de Chile inaugurates its undergraduate program (leading to a Licentiate degree) as the first of its kind in Chile. In 2003 Master and Doctorate programs in astrophysics are added.

1998: The construction of the first telescope of the VLT Observatory, located on Cerro Paranal at 2635m above sea level in the Antofagasta Region is finished. In 2002 the last of a total of four observatory telescopes is completed. The four telescopes receive names in Mapuche language; the first one is called Antu (Sun), and the following telescopes are Kueyen (Moon), Melipal (Southern Cross) and Yepun (Venus).

1999: The Universidad de Chile creates a PhD program in astrophysics.

1999: The Universidad de Valparaíso introduces a new undergraduate program in physics with major in astronomy. After five years, in May 2004, faculty members decide to organize the first astronomy research group at the university.

1999: The Cosmic Background Imager (CBI) is the first radio-telescope on the Chajnantor plateau. CBI operates until 2010.

2001: The Universidad de La Serena opens an undergraduate program in physics with minor in astronomy.

2002: On January 18, the Gemini South Telescope is inaugurated on Cerro Pachón, near Cerro Tololo.

2002: The Atacama Submillimeter Telescope Experiment (ASTE) is installed in the sector Pampa La Bola on the Chajnantor Area. This telescope is a pioneer telescope for the NAOJ submillimeter interferometry project (LSA).

2003: The Atacama Pathfinder Experiment (APEX) is installed in Llano de Chajnantor, 50km east of San Pedro de Atacama. APEX is the result of collaboration between the Max-Planck Institute for Radioastronomy (MPIfR), the Onsala Space Observatory (OSO), and ESO. The telescope is operated by ESO. APEX is the pioneer project for ALMA, the Atacama Large Millimeter / Submillimeter Array, a new and revolutionary telescope that it being built in are Llano de Chajnantor.

2004: In April 2004, the Brazilian SOAR Telescope, an optical and close-range infrared telescope on Cerro Pachón is inaugurated. Its main structure is a 20m diameter dome which houses the main mirror with a diameter of 4.1m and a width of 10cm.

2006: The National Commission for Scientific and Technological Research (CONICYT) creates its Astronomy Program with the intention to promote national development in astronomy and related scientific areas.

2007: The Atacama Cosmology Telescope (ACT) is built on the slope of Cerro Toco at 5200m altitude on grounds belonging to the Parque Atronómica de Atacama. The goals of the ACT project are to study how the universe began, what it is made of, and how it evolved to its current state.

2009: The 1m - mini TAO (Tokyo Atacama Observatory) is installed in Cerro Chajnantor at 5600m altitude, an area which forms part of the Parque Astronómico Atacama Project administrated by CONICYT. This instrument which will study the origin and evolution of the universe will be the infrared telescope located at the highest altitude worldwide.

2011: Universidad Andrés Bello launches its undergraduate program in astronomy.

2011: Polarbear is a microwave telescope outfitted with a large imaging camera deployed in Cerro Toco. It is built and operated by Berkeley University with a multinational collaboration of universities and labs. The instrument is designed to image the polarization of the microwave sky. Its goal is to investigate the origin and evolution of the universe in order to understand physics and cosmology beyond the standard model.

Under construction:

(2012): Atacama Large Millimeter / Submillimeter Array (ALMA). This international association from Europe, North America, East Asia and Chile is the largest astronomic project. ALMA will be a unique telescope of revolutionary design and is initially composed of 66 high-precision antennas in Llano de Chajnantor at an altitude of 5000m. In 1995 NRAO/ESO/NAOJ in cooperation with Chile began testing in the area. In May 1998 the design and development phase started. In April 2003 the testing of the first antenna prototype begins. ALMA started observations in the second half of 2011 and should be fully functional by 2013.

(2012): LSST is currently in its pre-construction phase. During this phase NOAO is responsible for the design and development of the LSST telescope system and on-site installations. LSST will be located on Cerro Pachón, very close to the Gemini telescopes and SOAR. Gemini, SOAR and NOAO will share operational infrastructure on the mountain and in La Serena. The project started in 2005 but it is expected to be operative in 2014.

(2013): CCAT. This will be a 25m submillimeter telescope situated at 5600m altitude at Cerro de Chajnantor in Northern Chile. CCAT combines high sensitivity, wide-range vision, and long-range waves to provide unprecedented capacity.

(2018): GMT, Giant Magellan Telescope. The location of this 25m telescope will be the Las Campanas Observatory about 115km northeast of La Serena, where also the Magallanes telescopes are sited. Same as for the previous telescopes this site has been chosen for its year-round favorable climate.

(2020): E-ELT European Extremely Large Telescope. This ground-based telescope will have a 39.5m main mirror and will be the largest optical/near-infrared telescope in the world. It will be located on Cerro Amazonas at 3060m altitude.

APENDIX B

Historical Development of Astronomy in Chile

Astronomy in Chile started with the foundation of the National Astronomical Observatory in 1852. In that year, the Government of Chile purchased astronomical equipment, left after the successful mission of Lieutenant James Gillis from The US Navy in 1847 to measure the transit of the planet Venus, and installed an observatory on Cerro Santa Lucía in Santiago.

During the nineteenth and early twentieth century, the National Astronomical Observatory (OAN) was dedicated to astrometry and several high precision telescopes were purchased for this purpose. It was the first Latin American observatory and its astronomical research and activity was published in 30 scientific articles in international journals in Germany, England, and the US. Moved from Cerro Santa Lucía to Quinta Normal and then to Lo Espejo in the south west area of Santiago. The observatory was responsible for the astronomical plates of the southern skies. Between 1906 and 1913, 50 "cartes du ciel" were taken with one of the seven identical Gautier telescopes distributed around the world. It also provided services to the community such as legal advice and the Chilean official time standard. In 1927 the National Astronomical Observatory was transferred from the Ministry of Education to the Faculty of Mathematical and Physical Sciences of the Universidad de Chile. Today it can be found on Cerro Calán, which is the location of the Astronomy Department created in 1965.

Parallel to these developments, another US mission from Lick Observatory arrived in Chile in 1903. They installed a telescope at the summit of Cerro San Cristóbal and for 26 years obtained spectra of stars. In 1929 the observatory was purchased by Dr. Manuel Foster who donated it to the Pontificia Universidad Católica de Chile.

In 1918 an expedition from the Smithsonian Astrophysical Observatory was sent to Calama, Chile, to conduct observations to measure the solar constant. The expedition was in charge of Mr. A. F. Moore, director, and his assistant Mr. L. H. Abbot. The solar constant of radiation was observed on 123 days out of a possible 170 days and an average value of 1.951 calories/cm-2/s was obtained.

The beginning of astrophysics. Federico Rutllant, Director of the OAN between 1950 and 1964, had a decisive influence on the development of Chile as the astronomical capital of the world. He convinced astronomers from Chicago to visit Chile when they were looking for a place in the southern hemisphere to locate the first international observatory. Chilean astronomers were involved in the search for mountains, apt for astronomical research and as a location for the observatory. In 1968 the Cerro Tololo Interamerican Observatory was set up near La Serena in the fourth region. Following Cerro Tololo, the Carnegie Institution of Washington installed the Las Campanas Observatory and the European Southern Observatory (ESO) constructed the La Silla Observatory in the same region. Thus, at the beginning of 1970, three major international observatories were operating in Chile. The dark southern skies were open to discoveries and the physical study of the universe (astrophysics) started.

With the inauguration of the first optical observatories, Universidad de Chile signed international agreements and started collaborations with different US universities and other institutions around the world. Chilean observatory staff went to the US to get PhD degrees in astronomy; and in collaboration with the Florida University, the Maipú Radio Astronomy Observatory, the first radio observatory in Latin America, was constructed in 1959. A scientific collaboration with the National Academy of Science of the former USSR resulted in the construction of the Astronomical Station at Cerro El Roble in Chile´s fifth region, where the Maksutov Astrograph Telescope was installed. The observatory staff performed many observations and published their results in international journals.

In 1965 the Universidad de Chile created the first Astronomy Department to train a generation of astronomers that would use the new powerful telescopes being installed in the country. The BS degree (licenciatura) in Astronomy was created and the university's astronomy students were able to continue with PhD studies with fellowships provided by American organizations running the observatories in Chile. In particular, Las Campanas Observatory provided Carnegie fellowships until 2000. Following the formation of the first generation of PhD Chilean astronomers, the Astronomy Department of the Universidad de Chile created a MSc in Astronomy in 1976 and a PhD program in 1999.

In 1980 the Pontificia Universidad Católica de Chile started an astronomy group that evolved into the university's Astronomy and Astrophysics Department by 1996. The new Department launched a BS program in astronomy in 1999 and a PhD program in 2003. Since 1990 several other universities have followed, creating astronomy groups and/or departments.

***The consolidation period;* the 8m class telescopes.** After the three international observatories had been in operation in Chile for almost 20 years, new projects with more powerful instrumentation were being developed around the world. These projects would increase the telescopes size from four to eight meters in diameter. The Chilean skies had proved to be excellent for astronomical research. Also, the favorable conditions of operation that the observatories had been granted and the stability of the country made Chile the preferred place in the southern hemisphere to install new larger telescopes with more sensitive detectors.

Thus, between 1990 and 2000, ESO developed the Paranal Observatory near Antofagasta to host the four 8m VLT telescopes. The Carnegie Institution of Washington together with private university partners constructed two 6.5m telescopes, the so-called Magellan telescopes, and installed them at Las Campanas Observatory. The international Gemini Consortium, with seven countries including Chile, decided on the construction of two twin 8m telescopes, one to be located in Mauna Kea, Hawaii and the other one on Cerro Pachón, near Cerro Tololo. These new telescopes and observatories began their operation in 2000.

Meanwhile, investigation of the high altitude region near San Pedro de Atacama proved the area to be unique for research in the IR, millimeter and submillimeter domain, complimentary to optical studies. In 1998 the Chilean Government declared the Llano de Chajnantor at 5000m altitude a scientific preserve for astronomical studies, and endorsed a 5-year concession to CONICYT for its administration; the concession was renewed in 2005.

During this period, the astronomical activity in Chile was increasing. A private entity, Fundación Andes, supported the development of astronomy, providing co-funding for fellowships offered by the UK funding agency PPARC and the North American partner AURA to Chilean PhD students in the UK and North America. Fundación Andes also sponsored collaboration agreements between PhD programs at Universidad de Chile and Yale University, and Princeton University and Pontificia Universidad Católica de Chile, and provided grants to young astronomers to reinsert in Chilean universities. At the same time, astronomy students from Chilean Master's programs were able to obtain PhD fellowships in the most prestigious universities in the US.

In 1996 the Government of Chile and ESO created a development fund as part of the negotiations to modify the original agreement of 1964 for the establishment of the new Paranal Observatory. This modification included guaranteed 10% of telescope time for Chile in all ESO telescopes and the creation of an annual fund. The ESO-Chile fund encouraged new astronomy groups by financing the first two years of a new faculty on the condition that the position would be continued by the university, and provided funding for postdoctoral positions and for the development of astronomical instrumentation.

By the end of 1999, Universidad de Chile, Pontificia Universidad Católica and Universidad de Concepción offered astronomy careers. A total of 25 faculty where supporting BS programs, Master´s programs and incipient PhD programs in astronomy. The opening of the BSc in Astronomy at Universidad Católica showed the increased interest of students in astronomy as the score on the Chilean national test for university applicants exceeded the score required by engineering faculties which was the historical way to pursue studies in astronomy.

During the last decade, some of the largest and most important international observatories and astronomical projects have commenced operation, site testing or construction in Chile. Since 2000, at least eleven astronomic projects were set up or planned to be set up on Chilean territory, including small telescopes which can be considered astronomical experiments and new large and very large telescopes.

In 2002 the Gemini South Telescope was officially inaugurated. One year later, in 2003, the construction of the Atacama Pathfinder Experiment telescope, APEX, on the Chajnantor plateau in Chile's Atacama region was started. APEX, which saw first light in 2005, is the largest submillimeter-wavelength telescope operating in the southern hemisphere, and considered to be a pathfinder for ALMA, the Atacama Large Millimeter / Submillimeter Array. During the same year, the National Assets Ministry, ESO and the Association of Universities Inc. (AUI) signed an agreement which provides a 50-year concession for an area of approximately 18 thousand hectares on the Chajnantor plateau for the installation of 66 high-precision antennas, composing ALMA. ALMA is expected to be inaugurated during 2013, and its construction to be completed in 2014.

In April 2004 Brasilian telescope, the Southern Astrophysical Research (SOAR) Telescope on Cerro Pachón was inaugurated. SOAR is a 4.1m aperture telescope designed to work from the atmospheric cut-off in the blue (320nm) to the near infrared and to have up to nine instruments mounted ready for use. It was funded by the Ministério da Ciencia e Tecnologia of the Federal Republic of Brazil (MCT) in partnership with the US National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU).

In 2007 the Atacama Cosmology Telescope (ACT), a collaborative project of ten countries including Chile, was built on Cerro Toco at 5200m altitude on grounds administered by CONICYT. The telescope uses one instrument, which is expected to be upgraded in 2013. Two years later, in 2009, the University of Tokyo installed another small experimental telescope on Cerro Chajnantor on CONICYT-grounds. The 1m-telescope forms part of the Tokyo Atacama Observatory Project (TAO), and is expected to be followed by a larger investment in a 6.5m telescope. Other smaller telescopes under way include Polarbear, a microwave telescope installed on Cerro Toco at the end of 2011 and CLASS which will also be set up on CONICYT-ground.

Also in 2006, after three years of site-testing in Europe, the United States, and South America the LSST Corporation, formed by an important number of international universities, made the decision to locate a new telescope on Cerro Pachón, near La Serena, favoring Chile over candidate sites in Southwestern US, Baja California Mexico, the Canaries, and Hawaii. The 8.4m Large Synoptic Survey Telescope (LSST) is a wide-field telescope facility; the telescope is currently in its pre-construction phase and is expected to be ready for operation in 2022.

During the same year, 2006, intensive site-testing for the CCAT Observatory started. In 2008 Cerro Chajnantor at 5600m was defined as the final location for the 25m telescope for submillimeter astronomy. CCAT is considered to be an essential complement to ALMA and was ranked the highest priority among medium scale, ground based projects by the Astro2010 survey. The CCAT consortium includes Cornell University; the California Institute of Technology (Caltech) and the Jet Propulsion Laboratory, which is managed by Caltech for NASA; the University of Colorado; the University of Cologne and the University of Bonn; McGill University, McMaster University, the University of British Columbia, the University of Calgary, the University of Toronto, the University of Waterloo, Dalhousie University and the University of Western Ontario; and Associated Universities Inc. Construction is projected to begin in 2013 and end in 2020.

Another large telescope under way is The Giant Magellan Telescope (GMT), a project led by an international consortium of leading universities and science institutions. GMT is considered to be one of the next class of super giant earth-based telescopes, and will be located on Las Campanas Observatory property. It will be operational in about 10 years. Civil works at the summit of LCO where started in March 2012.

Finally, Chile is expected to host the world-largest optical/near-infrared telescope planned so far. In 2011 the Chilean Government signed an agreement with ESO concerning the transfer of 18.9 thousand hectares and a free concession of further 36.2 thousand hectares in the central part of Chile's Atacama Desert for the construction of the European Extremely Large Telescope (E-ELT). The selected site, Cerro Armazonas is an approximately 3060m high mountain and about 20 kilometers from Cerro Paranal, home of ESO's Very Large Telescope (VLT). E-ELT is a revolutionary scientific project for a 39.5m telescope. Preparatory construction work on some of the E-ELT's first elements will commence in early 2012. The final approval of the whole E-ELT program by ESO Council is expected in mid-2012, which will enable the E-ELT to start operations as an integrated part of the Paranal Observatory early in the next decade.

APENDIX C

Questionnaire for Universities in Chile: Research & Development of Astronomy-related Technology [1]

Background

Beginning in May 2011, a working group chaired by the Astronomy Program at CONICYT and composed of officers from the National Commission for Scientific and Technological Research (CONICYT), The Ministry of Economy, Corfo/InnovaChile, and consultant Dr. Gary Sanders from the Thirty Meter Telescope, has been charged with the task of evaluating the current capabilities in Chilean industry and university research relating to the development and production of technology with applications in the field of astronomy, as well as possible synergies with other sectors including Mining, Agriculture and Defense. The goal of this project, primarily, is to discern what degree of collaboration exists today between Chilean industry and universities in developing technology for the international astronomical observatories in Chile, in addition to discovering ways to further improve and stimulate partnerships between universities, industry and observatories cooperating in research and development initiatives that might lead to spin-offs with prosperous applications in a variety of sectors of the Chilean economy.

Areas of interest include but are not limited to: astronomical instrumentation (detectors at various spectral bands, spectrographs) CCDs, photonics, instrumentation for the monitoring of atmospheric variables, software and mathematical modeling programs designed to forecast atmospheric parameters of interest for the operation of observatories, software for large volume data-handling, data mining, numerical simulations, control systems, automation & robotics, cryogenics & cryostatistics, opto-mechanics, lasers, adaptive optics, signals research, etc.

At present, the aforementioned working group is collaborating with major international observatories in Chile to gain insight into their needs in terms of staff, researchers, equipment and technology as well as their experience with the expertise and capabilities of Chilean companies in the field. With that in mind, we have prepared the following questionnaire in order to learn more about the current status of research and technological development in astronomy-related university labs and research centers in Chile.

We invite you to answer this questionnaire as means of sharing your experience, input and advice with the working group. All information gathered will be used exclusively to address in a more complete manner the mandate of the working group, in terms of including the university perspective on astronomy in Chile, and to make future recommendations to relevant sectors of the government. Thank you in advance for your time and thoughtful responses.

Research and Technology

1. What areas of research and technology development do you currently focus on in labs or research centers run by your department (particularly those areas with applications in astronomy)?

2. How many years have your labs or research centers been in operation?

3. What staff (professors, postdocs, graduate students, undergraduates) currently work in your department? Please include figures for each as well as relevant information on academic degrees, professional titles, and where they received their education.

4. How involved are students with the research taking place at your labs? In what capacities do they work on experiments and the development of technology?

Are there any student initiatives / groups with relevant investigation or development activities at your university? How are they organized and what kind of support (e.g. guidance by faculty members, access to infrastructure) do they receive?

What partnerships does your department have with universities or research groups outside Chile? What types of projects have you undertaken together? Include internship programs, foreign faculty visitors, and researchers on sabbatical?

5. Has your department engaged in projects developing technology for astronomical observatories, the mining industry and/or the defense sector or other (particularly in Chile)? If so:

6. What kinds of projects were undertaken?

7. How long did the project take to complete and who were your collaborators?

8. What kind of equipment and instrumentation do you use for your research? Please list in detail equipment and instrumentation currently being used for projects in your department/labs. Include other facilities i.e. International Observatories, International Labs, etc.

9. How has the size of your department changed in recent years with regards to size of staff, number and size of labs, number of projects undertaken, equipment available, etc.? Please provide figures if possible. What do you feel is most lacking for your lab/research center to compete internationally? Could you mention an equivalent international lab/department to yours.

1 This questionnaire was sent to universities following a breakfast meeting organized by the Ministry of Economy in July 2011.

10. How many patents have your department and associated labs filed in recent years and for what projects? Do you foresee filing any patents in the near future for ongoing research? Please provide a list of the main publications that have resulted from your research in the specific area of technology development (conceptual as well as developmental).

11. Has the presence of international observatories in Chile and their growth in recent years impacted on your department development? Please explain.

12. What are your main sources of funding (public and private), indicate percentages.

Relation with Industries

13. What partnerships does your department have with companies in Chile for research or the development of technology (particularly on projects with applications in astronomy)? What is the nature of the partnership and what types of projects have your undertaken together?

14. Do you foresee any spin-offs or possible novel applications of your research either in the commercial sector or for use in observatories, in terms of technology developed for other purposes?

15. What further support and/or resources are needed to pursue research on new applications of the technology developed at your lab or to realize new conceptual projects? What do you feel is most lacking in terms of being able to realize your department´s full research potential (i.e. human expertise, funding, opportunities for collaboration, access to equipment and infrastructure, etc.)?

General

16. What are your suggestions or advice on how the government might help to boost the development of astronomy-related technology in Chile, as well as foster industrial spin-offs of research in the field?

17. Would you be willing to share your experience with projects you consider most successful and that may serve as a benchmark for future projects.

Note. Please send your responses to **azuniga@conicyt.cl** before September 1st, 2011

APENDIX D
Information on Universities

Between August and November 2011, the Roadmap working group sent out a special survey to universities with activities in astronomy and astronomy-related projects. Six universities answered the questionnaires and were invited to follow-up meetings between September and November 2011. The following table shows the list of universities which responded to the questionnaire and provided extensive information on their activities.

Table: Contact information of university groups and centers

University	Group, Laboratory or Center	Contact	Position	Email
Universidad de Chile	Millimeter-Wave Laboratory	Leonardo Bronfman	Team Leader	leo@das.uchile.cl
Universidad de Chile	Photonics Laboratory	Ernest Michael	Associate Professor	emichael@ing.uchile.cl
Universidad de Chile	Center for Mathematical Modeling (CMM)	Eduardo Vera	Innovation Manager	esvera@dim.uchile .cl
Pontificia Universidad Católica de Chile	Center for Astro-Engineering	Leopoldo infante	Director	linfante@astro.puc.cl
Universidad de Concepción	Radio-Astronomy Laboratory	Neil Nagar	Associate Professor	nagar@astro-udec.cl
Universidad de Concepción	Center for Optics and Photonics	Sergio Sorbazo	Researcher in optoelectronics	sergio.sobarzo@cefop.udec.cl
Universidad de Valparaíso	Center of Astrophysics of Valparaiso	Radostin Krutev	Director	radostin.kurtev@uv.cl
Universidad Católica del Norte	Astronomy Department	Rolf Chini	Director	rolf.chini@gmx.de

Additionally Dr. Eduardo Vera, Director from the Center for Mathematical Modeling (CMM), a center of excellence run by the Universidad de Chile and Universidad de Concepción was invited to provide input in March 2012.

The following chapters summarize the information compiled through surveys and interviews.

Organization and Research

The fact that the world largest telescopes operate and will operate in Chile has had a large impact on universities. During the last 30 years, not only new astronomy related careers and postgraduate programs have been set up, but staff has grown rapidly and traditional universities have become increasingly involved in areas such as instrumentation and computing. Aware of the opportunities for the development of high technology in Chile, astronomy departments in large Chilean University have started combining efforts with other departments such as Electrical Engineering, Computer Sciences and Physics by setting up joint groups, laboratories or centers of excellence. Through these centers or groups, universities have collaborated with international observatories and leading universities in the evaluation of sites, construction of parts of instruments and development of data processing solutions. Research on instrumentation covers areas such as adaptive optics, spectrograph, and receivers. Computational solutions developed by university groups include algorithms for telescope alignment and computing capabilities for data processing, data mining, and high volume data transfer, among others. The following table shows information collected on initiatives and research activities in six Chilean universities.

Table: University groups and primary research areas

University	Research Organization (Centers, groups, labs)	Founding Year	Primary Research Area
Universidad de Chile	Millimeter-Wave Laboratory, run by the Astronomy Department, the Electrical Engineering Department, and the Faculty of Physical and Mathematical Sciences at the National Astronomical Observatory on Cerro Calán.	2004	•Design and construction of state-of-the-art mm-wave receivers, front-end components, and digital spectrometers.
Universidad de Chile	Photonics Laboratory at the Electrical Engineering Department.	2008	•Photonics system and devices. •Radio frequency receivers in corporation with the Department of Astronomy. •Systems and devices for space physics.
Universidad de Chile	Center for Mathematical Modeling (CMM): •Astroinformatics Laboratory •National Laboratory of High-Performance Computing (NLHPC)		•Automated detection and classification of astronomical objects. •Analysis and classification of transient events. •Reconstruction of interferometric images. •Handling and modeling of astronomical data. •Mathematical modeling, data mining, statistics, image processing, data visualization, data processing and storage in general.

University	Research Organization (Centers, groups, labs)	Founding Year	Primary Research Area
Pontificia Universidad Católica de Chile	Center for Astro-Engineering (AIUC) is a jointly run by the Department of Astronomy and Astrophysics (DAA) and the Department of Electrical Engineering with participation of the Departments of Computer Science and Physics.	2010	• High resolution optical and NIR-echelle spectrographs. • Adaptive optics (wide-field, beam shaping, Cn2 characterization). • Design and fabrication of cryogenic cameras, scientific CCDs and NIR detectors. • Fiber optics. • Astronomical site testing. • Telescope performance evaluation (Cosmic Microwave Background, ACT, ACTpol). • High performance computing, numerical simulation, data base management. • Planet finding as part of Hat-South network a network of six identical, fully automated wide field telescopes, located at three sites (Chile, Australia and Namibia).
Pontificia Universidad Católica de Chile	Department of Astronomy and Astrophysics (DAA) research groups: • VVV group • Cosmological Simulation Group • SNe group • ACT CACTUS group • NIT spectroscopy group		• Basic research in observational, theoretical, computational astrophysics.
Pontificia Universidad Católica de Chile	Department of Electrical Engineering		Research with links to astro-technology: • Industry and medicine: Spectrometers for online sensors (wood, wine, copper mining), magnetic resonance imaging (wood 3D Fourier alg.), visual sensors, visible 6 infrared. • Defense: Radar signal processing, tracking systems, servo systems for mount positioning and pointing.
Universidad de Concepción	Radio-Astronomy Laboratory	2009	Instrumentation related projects: • Millimeter-VLBI. • Radiometers 183GHz (refurbishment, site testing and characterization). • Radiometer development (for weather forecasting, data calibration, site testing).

University	Research Organization (Centers, groups, labs)	Founding Year	Primary Research Area
Universidad de Concepción	Center for Optics and Photonics (2010): • Optoelectronics Laboratory (2007) for research on sensor systems (sensor arrays, optical detectors) • Optics and Quantum Information Laboratories	2007	Infrared Imaging: • Hyperspectral Imaging: Software, hardware design and implementation, calibration. • Applied Radiometry: Flame spectral models. • Optical Sensors • eVLBI Data Transferring: Multirouting and custom transport protocols. • Optical interferometry, including long distance microwave antenna design.
Universidad de Valparaíso	Center for Astrophysics of Valparaiso (CdAV): • Astrometeorology group	2006	• Meteorology techniques in macro and micro scale for observatories.
Universidad Técnica Federico Santa María	IT Department: • Computer Systems Research Group (CSRG)	2004	• Contributions to ACS. • Uniform software interface for flexible telescope control system (gTCS).
Universidad Católica del Norte	Institute of Astronomy	1996	• X-ray spectroscopy and imaging of active galactic nuclei. • Optical spectroscopy of early type stars and the interstellar medium. • Photometry of stars and active galactic nuclei.

International Collaboration and Partnerships

Chilean universities have established a number of agreements with universities and research institutes in the United States, Canada, Europe and to a less extent in Asia and Latin America to promote academic and student exchange at postgraduate level and cooperation in research projects. The following table gives an overview of contacts reported by universities as part of the university survey.

Table: Contacts of Chilean universities with foreign universities, research centers and observatories

University	Partner Institutions and Observatories	General Description
Pontificia Universidad Católica de Chile	University of Durham (UK); Gemini Observatory; Harvard Smithsonian Center for Astrophysics (CfA, USA); ACT (Princeton, Rutgers, Penn State, BC Universities); VLT; ESO; INAF (Italy).	Academic and student exchange. Design and construction of instrument parts, characterizations, etc.
Universidad de Chile	CalTech-JPL (US); University of Cologne (Germany); Herberzg Institute for Radio Astronomy (HIA, Canada); Group for Advanced Receiver Development (GARD) and Physical Electronic Laboratory (MC2) - Chalmers University (Sweden); TU Delft (Netherlands) ; STFC Rutherford Appleton Laboratory (RAL; UK); the Netherlands Institute for Space Research (NOVA/SRON); Academia Sinica Institute of Astronomy and Astrophysics (ASIAA, Taiwan); University of Manchester (UK); Yebes Astronomy Center (Spain); MIT-Haystack (USA); Cornell University (USA); Boston University (USA); Taylor University; Upland (USA); University of Michigan (USA); Georgia tech (USA); University of Washington (USA; Universtiy of Napoli (Italy); SRI International, Palo Alto (USA); APEX; Polarbear; CCAT; ALMA; QUIET; AURA.	Academic and student exchange. Projects for construction of millimeter and submillimeter receiver components, site testing and development of parts for observatories, and photonics. Joint research developed by the Astroinformatics Laboratory in CMM. Special topics meeting and symposium.
Universidad de Concepción	Electrical and Computer Engineering Department of University of New Mexico (USA); Astronomic Department of Caltech (USA); Aerospace Department of University of Liege (Belgium); Center for Telecommunications Studies at the Catholic University of Rio (Brazil).	Academic and student exchange. Joint research (no specification).
Universidad Técnica Federico Santa María	NRAO; ALMA; VLT; La Silla; Paranal Observatory; Gemini Observatory; PUC; UV.	Computation, software development.
Pontificia Universidad Católica de Chile	Institute for Astronomy University of Bochum (Germany)	Time-sharing agreement for telescope at Cerro Murphy.

Larger universities with more faculty members and centers have used academic exchange and partnerships with foreign institutions as a way to get involved in the development of parts of instruments and other project contributions. The following tables show research areas and projects developed by the Pontificia Universidad Católica and the Phototonics Laboratory of Universidad de Chile in collaboration with foreign institutions.

Table: Partnerships and joint research projects developed by faculty from the Pontificia Universidad Católica de Chile

Partner Institution	Type of collaboration	Research areas
University of Durham (UK)	Joint research, academic exchange	• Tomographic reconstruction for multi-object adaptive optics. • Pre-conceptual design of an instrument for ESO. • New instruments for turbulence profiling for ELT scales.
Gemini Observatory	Joint research	Multi-conjugate adaptive optics instrument at Gemini South using: • Laser beacons to implement SLODAR techniques for Cn2 characterization. • Vibration mitigation for the instrument.
Harvard Smithsonian Center for Astrophysics (CfA, USA)	Partnership	• Design and construction of the two cryogenic focal planes for G-Clef instrument and the Exposure Time Calculator.
ACT (Princeton, Rutgers, Penn State, BC Universities)	Partnership	• Submm Telescope El Toco.
VLT, international consortium	Partnership	• MOONS, Spectrograph MOS NIR.
VALTEC (V. Suc)	Partnership	• Approved patent for telescope 0.5m.
INAF	Partnership	• Phase A study of SIMPLE, a high resolution near IR-echelle spectrograph for the E-ELT. The study was carried out by an international consortium led by INAF (Italy). • With the support of INAF a Laboratory of infrared technology was created.

Table: Partnerships and joint research projects developed by the Photonics Laboratory of Universidad de Chile

Partner Institution	Type of collaboration	Research areas	
Chalmers University of Technology (Sweden)	Training and consultation, access to lab facilities	Physical Electronics Laboratory at the Department of Microtechnology and Nanoscience (MC2): • Training and consultation for micro-fabrication of novel travelling-wave UTC photodiodes for terahertz generation.	Photonics Systems and Devices
ITME (Poland)	Joint research	• Growth of specialized semiconductor wafers for micro-device fabrication at cleanroom facilities.	
TU Delft (Netherlands)	Joint research, access to lab facilities	• Micro-fabrication of novel travelling-wave MIM-junctions for THz-generation.	
NRAO New Technology Center Charlottesville (USA)	Consultation and joint research	ALMA Photonics and Backend Laboratory: • Consultation support in technical questions on the photonic system of ALMA • Support for research on risk mitigation and upgrade projects for ALMA.	
CCAT team, Cornell University (USA)		(Collaboration, not further specified.)	
University of Cologne (Germany)	Joint research	• THz-spectroscopy, loaned 780 nm dual-laser optics for LT-GaAs photomixer testing • Optically pumped FIR-Ring laser for THz-detection-device testing. • General collaboration and support.	
Boston University (USA)	Joint research	Center for Space Physics: • Modeling and simulation of unstable plasma at the auroral region.	Systems and Devices for Space Physics
Embry-Riddle Aeronautical University (USA)	Joint research	• Modeling and simulation of unstable plasma at the auroral region.	
Taylor University, Upland, Indiana (USA)	Joint research	• Construction of a Langmuir Probe to be placed in the CubeSat under development by the group.	
SRI International, Palo Alto (USA)	Joint research	• Search for Langmuir harmonics signatures in Incoherent Scatter Radar spectra at auroral region.	

Relationship with Industry and Patents

Relationships between university groups and industry are few. Even though university groups recognize the relevance of research and technology developments for other sectors, such as defense and life science industries, contacts to companies or spin-offs are relatively uncommon. Similarly, the number of patents filed and reported by groups is low. Only Universidad de Concepción stated to have filed two patents as a result of FONDEF and Innova projects.

Exceptions are spin-offs developed by Dr. Guzmán and Dr. Guesalaga at Pontificia Universidad Católica de Chile: Astroinventions offers cryogenic cameras, and DESA SA provides electronic control systems and signal processing for the defense sector. Also it was mentioned that individual AIUC members had partnerships with the local wine and mining industry. Universidad de Chile reported to have cooperated with a company for the outsourcing of components. Obstacles for industry collaboration, identified by the universities, include the particularity and complexity of technical requirements that needed to be fulfilled for astroengineering projects. Thus, Universidad de Chile stated to have established joint work between the university's laboratory team and the company in order to achieve the optimal thickness of a gold layer for a low noise amplifier.

Nevertheless, by organizing special topics meeting and symposia, centers of excellence which historically have had more interaction with industry, such as the Center for Mathematical Modeling (CMM) have drawn the attention of international researchers and industry to research and development conducted for astronomy. As CMM states, the Pucón Symposium, organized biannually since 2009 in cooperation with the National Research University Network (REUNA), ALMA, and AURA, and sponsored by CONICYT, has become a successful international conference focused on mathematical and computational tools as well as engineering and technological aspects, attracting the interest of researchers in areas such as astronomy, mining, natural resources, and biosciences.

University groups identified the following (unexploited) opportunities for spin-offs and the development or transfer of applications for other industries:

- Hardware and software applications for telecommunications (Universidad de Concepción).
- Optical sensors and technology for telecommunications (Universidad de Concepción).
- Numerical models developed as part of meteorological models for the energy and mining sector (Universidad de Valparaiso).
- Application of software features such as graphical interface to other systems (Universidad Técnica Federico Santa María).
- Application of adaptive optics, high speed and high sensitivity detectors for the defense and life science sectors (Pontificia Universidad Católica de Chile).
- Beam pattern measuring for telecommunications (Universidad de Chile).
- THz sources and detectors for imaging application in medicine, modular clean areas and hoods (Universidad de Chile).

Staff

Depending on the organization of research and development activities, universities employ between two and thirteen faculty members, who contribute to the work of labs, groups and technology centers. Postdocs, PhD candidates, and in some cases master and undergraduate students represent an important support for those groups. Also, engineers were reported to play an essential role in technology projects. However, both, the number of Postdocs and engineers were considered to be insufficient by universities. Only three universities, Universidad de Chile, Universidad de Concepción and Pontificia Universidad Católica de Chile offered Postdoc positions in research groups and labs; two at Pontificia Universidad Católica, and one each in the other two universities.

A special case is the Computer Systems Research Group (CSRG) at Universidad Técnica Federico Santa María. CSRG congregates different student research initiatives, such as ALMA-UTFSM. While research groups receive guidance by faculty members and access to labs, offices, and necessary equipment, the organization and implementation of research and development projects relies mostly on students, including a fair number of undergraduate students.

Funding

University research groups and centers rely heavily on public funding. At least 50% of financial resources come from public sources, including CONICYT funding for centers of excellence, FONDECYT and resources from CONICYT-ALMA and CONICYT-Gemini funds. University groups which are directly involved with observatories may get some direct financing.

Needs and Suggestions

Universities considered they were lacking sufficient long-term funding for human resources, equipment and infrastructure. Larger and more flexible funds were necessary to

- Attract experts, providing internationally competitive compensations.
- Provide a larger number and more stable Postdoc positions with competitive salaries.
- Allow the hiring of engineers and other specialized personnel.
- Provide support for qualified students and PhD scholarships.

Also, larger funds were needed to finance new and update necessary infrastructure, including physical space, and equipment, which were considered to be a bottleneck in most universities. Scientists considered that sequential fund applications pursued as a way to cover financial requirements of larger projects under the current system were a significant obstacle, and causing a substantial slow-down of research processes. In order to develop even small instrumentation significantly larger resources were needed.

It was suggested to conduct a survey of academic groups, identify most successful groups and/or instrument proposals and provide significant financial support to these initiatives.

APENDIX E

Questionnaire for Astronomical Observatories: Structure and Needs of Observatories Operating and Under Development in Chile

Following a meeting at the Ministry of Economy with representatives from observatories the following letter and questionnaire was sent to Dr. Thijs de Graauw (ALMA), Dr. Yasuo Fukui (NANTEN2), Dr. Eduardo Hardy (AUI/NRAO), Dr. Massimo Tarenghi (ESO), Dr. Anthony C.S. Readhead (Chajnantor Observatory), Dr. Miguel Roth (Las Campanas), Dr. Chris Smith (AURA), Dr. Ken Tatematsu (former representative of NAOJ in Chile) and Dr. Yoshii Yuzuru (TAO) between July 25 and July 26:

“Dear ...,
Thank you very much for joining us at the meeting last week at the Ministry of Economy. We are extremely grateful for your input and assistance moving forward in our efforts to stimulate the growth of research, industry and education surrounding the astronomical facilities here in Chile.
With the observatories already in operation in the North and many more under construction, we hope that the coming years will offer many chances for scientific and technological development and cooperation, as we strive to make Chile both a more prosperous country and the best possible environment for the world´s most ambitious and innovative astronomical projects.

With that in mind, we would greatly appreciate your help, as director for NRAO, in taking the time to see that the accompanying questionnaire – found at this link http://j.mp/astroquest – is filled out within the next four weeks (the questionnaire will be sent via email as well). The information gathered will comprise a major part of the Roadmap for the Development of Astronomy in Chile – a joint project between the Ministry of Economy, CONICYT, Innova-CORFO, the Ministry of Foreign Affairs and the National Innovation Council (CNIC). We invite you to join us in this effort and look forward to hearing your valuable input, not only by means of the survey, but also through a lasting partnership in the years to come.

On a separate note, we would also request that you fill out, the National Research and Development Survey, which you will be receiving shortly from INE (National Institute of Statistics). The survey is an attempt to catalog research and development efforts across many different industries and institutions in Chile. We ask that you do your best to respond to both questionnaires in the most detailed manner possible, and feel free to contact us with any further questions or comments.

Thank you again for your time and thoughtful responses. We are so grateful for your continued collaboration and help in seeking out new opportunities for astronomy, research and technological development to flourish here in the coming decades. The answers you provide will be the basis for new initiatives and hopefully many positive changes in Chilean industry and universities, to the benefit of both the country and the international astronomical projects based here.

We look forward to hearing from you very soon.

Sincerely,

Conrad Von Igel Grisar
Head of the Innovation Division
Ministry of Economy”

Research & Engineering Projects

18. What countries and/or universities are major participants in your observatory and how do they share use of your facilities?

19. Do these different groups conduct different research projects, bringing in a significant amount of their own staff and instrumentation? If so, is there any way Chilean researchers or firms might be able to get more involved with the development and production of new instrumentation for these projects?

20. What Chilean companies, if any, do you know of with the ability to manufacture specialized instruments or telescope parts developed for various research projects or the observatory in general?

21. What are your observatory´s main technological, operational and maintenance needs? (i.e. data management, cryogenics, optics, precision mechanics, software engineering, advanced construction services, etc.)

22. Are the any services or products your observatory frequently uses that could be more easily or less expensively contracted in Chile if the necessary expertise existed?

23. What sort of partnerships, if any, does your observatory maintain with universities or companies abroad and in Chile (specifically for developing specialized equipment and instrumentation and collecting and analyzing data)? What opportunities do you currently have or would you suggest in the future to help Chilean students and faculty become more involved with your work?

24. Has your observatory/institution provided support in any capacity (financially, research, travel grants, etc.) to Chilean students doing undergraduate or graduate work in Chile or abroad? If so, approximately how many students, in what fields, and what kind of support has been provided?

Governance and Procurement

25. Who is in charge of overseeing hiring and acquisition for large projects at your observatory?

26. Does the way your observatory is governed or funded constrain your selection of employees, service providers or industrial suppliers in any way? (i.e. Are you limited at all to awarding contracts based on the nationality of companies or universities, their involvement with certain governments or research groups, or a history of previous contracts?)

27. What is the process your observatory uses for procurement (listing projects and receiving bids)? Does the procurement system under which you operate provide equal opportunity and a level playing field for Chilean suppliers?

28. If your observatory is still under construction, are the majority of your large contracts already filled? Is there still opportunity for Chilean firms to place bids for any of your major contracts?

29. Does your observatory/institute keep a website with open contract opportunities? If so, has this system helped to get Chilean companies more involved in the bidding process? If no such website exists, do you have plans to create one in the near future?

30. What has been your experience (if any) with the technical quality, efficiency and administration of Chilean companies with whom your observatory has worked in the past? With

regards to projects that required advanced technical expertise or detailed specifications, how able were Chilean companies to carry out these projects on their own with satisfactory result?

Please provide, if possible, names of Chilean companies with whom you have had a particularly positive experience.

31. To the best of your knowledge, what kind of partnerships (if any) exist between international and Chilean firms contracted by your observatory? Do international firms, in seeking contacts, often employ local partners to carry out some or all of the work required?

Please provide, if possible, names of either international companies you have worked with who employ Chilean partners or subsidiaries or Chilean companies working in partnership with larger international firms.

32. In your opinion, what would be the best and most efficient way for Chilean companies to connect with foreign counterparts and explore possible business partnerships related to the needs of your observatory and others like it?

Budgeting and Contracts

33. Are you currently operating an observatory? (If not, please provide forecasted answers to the following questions, if possible, as well as a date when your observatory is slated to begin operation. i.e. simplified Gantt chart, significant milestones, etc.)

34. What is the approximate total investment in your observatory to date, including grants, startup funds, permanent installations, etc.? What percentage of that is spent in Chile?

35. What is the approximate annual operating budget for your observatory? About how much of this budget is spent in Chile, with Chilean contractors and employees?

Please provide, if possible, a rough breakdown of your expenditures with companies internationally and in Chile with regards to contracts with service providers and industrial suppliers, in addition to expenditures on collaborative research projects with universities in Chile and elsewhere.

36. What are the largest contracts you have currently filled or available for bidding?

Please provide, if possible, a list with a rough value for each contract, year it was issued, and whether the contract was fulfilled by a Chilean or foreign supplier. If you can also provide major considerations in choosing a bid (timetable, cost, part relationship with company, quality of service or product received) that would be very helpful as well.

37. Would it be helpful for your observatory to have a single point of contact with Chilean Industry (a liaison office of sorts) that could provide information on the capabilities of Chilean companies with regards to various products and services you might need?
Staff

38. What is the size of your staff both in Chile and abroad and what fraction of that staff is Chilean? In what positions are the majority of Chileans at your observatory employed, and what part of Chile are they from (if known)? (i.e. engineering, maintenance, software development, astronomers, researchers, administrative support, technicians, etc.)

39. What job positions are you typically looking to fill? Are there specific areas where Chile could grow or adapt its workforce to better meet your staff needs, particularly with regard to more high-level positions (researchers, engineers, technicians, etc.)?

40. Would your observatory be willing to collaborate with the Chilean government in seeking out new ways to incorporate Chilean workers and researchers into your workforce? Do you have any suggestions as to how best to move forward with this process (ideas for partnerships in technical training, research positions for Chilean students, new methods for seeking out service providers, etc.)?

41. What is the size of your temporary staff? What positions do the majority of your temporary staff occupy?

42. How many foreigners are currently working at your facilities (or expected to be working there in the near future)?

43. Future Needs and National Growth:

44. What is your projection of the most significant needs your observatory will have over the next decade that Chilean and foreign companies and/or universities might prepare for?

45. Do you have suggestions for how Chile, at a national level, could help stimulate such preparation and increase its ability to compete internationally, apart from specific funding or grants?

46. In what areas do you feel Chilean companies and/or universities lag furthest behind, with regards to the needs of your observatory and others like it? How might government or private initiatives improve on this gap?

Information from Observatories

Between August and November 2011, the Roadmap working group sent out a special survey to observatories located in Chile in order to compile information on organizational structures, operations, needs and opportunities for Chilean academy and industry. Two observatories answered the questionnaires and were invited to follow-up meetings between September and November 2011. The following table shows the list of observatories which received and responded to the questionnaire and provided extensive information on their activities.

Astronomy project	Contact	Position	Submitted response to questionnaire
TAO	Mamoru Doi	Project Scientist	Yes
ACT	Lyman Page	Director	Yes
ALMA	Thijs de Graauw	Director	No
NANTEN2	Yasuo Fukui	Director	No
ALMA, CCAT (AUI)	Eduardo Hardy	Legal Representative	No
Cerro Tololo, Gemini (AURA)	Chris Smith	Legal Representative	No
Chajnantor Observatory	Anthony Readhead	Director	No
Las Campanas (Carnegie)	Miguel Roth	Legal Representative	No
Paranal Observatory, La Silla, ALMA, E-ELT (ESO)	Massimo Tarengui	Legal Representative	No
ALMA (NAOJ)	Ken Tatematsu	Director	No
TAO	Yoshii Yuzuru	Director	Questionnaire responded by Mamoru Doi.

The following paragraphs summarize the information obtained from two observatories that responded, and the international consultants of the Roadmap.

Astronomy projects involve a number of processes, starting with the definition of science goals, its translation in science and technical requirements, and the development and selection of a design concept. Control fabrication and construction as part of final design needs to be documented before construction, integration and commissioning of the observatory can start. The overall process requires strong leadership and management skills, and each process requires expertise in diverse areas which is then translated into leading edge technology solutions.

In this environment, collaboration on specific parts of a project is based on particular expertise in one field and organizational solutions depend largely on astro-engineering models prevalent in each country. Thus, Chile needs to prove its ability to provide internationally competitive expertise in (niche) areas it wishes to participate and be able to establish relationships with decision-makers. As a result, Chilean participations, and in particular industry participation has been scarce and mostly concentrated in less complex areas such as site preparation, construction of facilities, assembling of telescope parts on-site and other support services, including housing, fuel supply and generator maintenance.

Both interviewed projects stated to have used Chilean companies for the construction of facilities. However, while the American project management had direct contact to Chilean companies, the Japanese project depended mostly on sub-contracting arrangements by Japanese companies which play an important role during the construction of the observatory and its technological solutions.

Participation of Chilean teams in the design and building of advanced technological solutions and instrumentation was less frequent. Opportunities arose as a result of specific expertise of university groups or individual researchers and relationships to project leaders. One example of this kind is the involvement of Ronaldo Dunner, an engineer from the Pontificia Universidad Católica de Chile and former doctorate student at Princeton, in the development of the receiver and alignment software for ACT, a project led by Princeton University. ACTs Project Leader, Lyman Page recommended to concentrate efforts in strengthening research capabilities in computation and instrumentation in Chilean Universities, rather than trying to establish specialized high-tech competencies in Chilean companies which he considered to be lacking furthest behind. According to Dr. Page, computation skills were easily obtainable in short-term, and widely applicable.

Another example is the recent agreement between the University of Tokyo and the Pontificia Universidad Católica which considers collaboration in the proposal for a fourth instrument for the 6.5m TAO-telescope, a project planned by the University of Tokyo. Concerning cooperation between Japanese and Chilean researchers in Japanese laboratories, Japanese project scientist Dr. Doi expressed that language was an important barrier as knowledge of Japanese was fundamental to participate in lab groups. At the same time, the Japanese Project leader expressed interest to establish academic exchange agreements with Chilean universities.

Both projects shared their concern and interest to outsource complex support services which did not form part of the core competencies of observatory teams, but were essential for operation. Specifically, projects share the need to have access to high capacity communication systems and reliable power systems for high altitudes. Currently, projects needed to solve both requirements by themselves.

APENDIX F
International Observatories

Optical / Infrared Telescopes

Name	A. Cerro Tololo Inter-American Observatory (CTIO)
Location	Cerro Tololo, 80km east of La Serena at 2200m altitude.
Region	Coquimbo Region
Associated Organizations	Association of Universities for Research in Astronomy (AURA) operates the observatory. AURA is an international association of universities: 34 are located in the United States and six are international (including two Chilean Universities: Universidad de Chile, Pontificia Universidad Católica de Chile).
Countries involved	Unites States, Chile.
Equipment (Telescopes)	Seven telescopes with diameters between 0.30m and 4m, eight robotic telescopes (PROMPT GONG, El Enano II) which are remote controlled by universities and entities in the United States.
Description	First international observatory in Chile.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption.
Funding / Contributions	National Science Foundation (NSF) from the United States and National Optical Astronomy Observatory (NOAO).
Total investment	USD 250 million
Legal Representative	Dr. Chris Smith
Director	Dr. Chris Smith
Phone	+56 (51) 205200
Fax	
Web site	www.ctio.noao.edu/

Name	B. La Silla Observatory
Location	160km north of La Serena on Cerro La Silla at 2000m altitude.
Region	Coquimbo Region
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere (ESO).
Countries involved	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, and Switzerland.
Equipment (Telescopes)	Three telescopes of 3.6 m, 3.5 m, and 2.2m respectively are operated by ESO. Two telescopes of 1.2m and 1.5m are operated by Switzerland and Denmark.
Description	First ESO observatory (1964). Its administration was combined with the Paranal administration.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption.

Funding / Contributions	ESO countries.
Total investment	EUR 200 million (Paranal / La Silla: EUR 900 million)
Legal Representative	Dr. Massimo Tarengui
Director	Dr. Andreas Kaufer
Phone	+56 (55) 435 000
Fax	+56 (55) 435 001
Web site	http://www.eso.cl/la_silla.php

Name	C. Las Campanas Observatory
Location	Cerro Manqui, near Cerro Las Campanas, 160km north of La Serena at 2500m altitude.
Region	Atacama Region
Associated Organizations	Carnegie Institution of Washington, Harvard University, Massachusetts Institute of Technology (MIT), University of Michigan, and the University of Arizona.
Countries involved	United States.
Equipment (Telescopes)	Magellan Telescopes I and II, 6.5m each, Dupont Telesope 2.5m, Swope Telescope 1m. The 24.5m Giant Magellan Telescope (GMT) is being constructed at a foreseen cost of USD 700 million in partnership with, Australia, and South Korea.
Description	Third oldest modern observatory in Chile after Tololo and La Silla.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption.
Funding / Contributions	Not published.
Total investment	USD 130 million
Legal Representative	Dr. Miguel Roth
Director	Dr. Miguel Roth
Phone	+56 (51) 203 626 (Mountain) +56 (51) 207 301 (La Serena Office)
Fax	
Web site	www.lco.cl

Name	D. Southern Astrophysical Research Observatory (SOAR Observatory)
Location	Cerro Pachón, 80 km from La Serena at 2700m above sea level.
Region	Coquimbo region
Associated Organizations	Brazilian Ministry of Science and Technology (MCT), National Optical Astronomy Observatory (NOAO), University of North Carolina at Chapel Hill (UNC), Michigan State University (MSU).
Countries involved	United States, Brazil.
Equipment (Telescopes)	4.1m diameter optical/IR-telescope, azimuthal type.
Description	4.1m diameter optical telescope.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption.
Funding / Contributions	Associated Organizations.
Total investment	USD 28 million
Legal Representative	Dr. Chris Smith
Director	Dr. Stephen Heathcote
Phone	+ 56 (51) 205293
Fax	
Web site	www.soartelescope.org/

Name	E. Gemini South Observatory
Location	80km from La Serena, near the summit of Cerro Pachón in central Chile, at an altitude of 2722m.
Region	Coquimbo Region
Associated Organizations	AURA (Association of Universities for Research in Astronomy) is the NSF executive agency for Gemini Observatories.
Countries involved	United States, United Kingdom, Canada, Australia, Brazil, Argentina, and Chile.
Equipment (Telescopes)	8.1m optical/infrared telescope.
Description	The Gemini consortium operates two identical telescopes, one in the Northern hemisphere (Hawaii), and one in the Southern hemisphere in Chile. It is optimized for infrared observations.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption. CONICYT hosts the Chilean Gemini office administering the telescope time.
Funding / Contributions	United States (NSF): 43.9%, United Kingdom: 22.0%, Canada: 13.9%, Australia: 5.7%, Argentina: 2.2%, Brazil: 2.3%, Chile: 10%.
Total investment	USD 200 million
Legal Representative	Dr. Chris Smith
Director	Dr. Nancy Levenson
Phone	+56 (51) 205 603
Fax	
Web site	www.gemini.edu/

Name	F. Paranal Observatory
Location	130km south of Antofagasta at Cerro Paranal at an altitude of 2400m.
Region	Antofagasta Region
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere (ESO).
Countries involved	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, and Switzerland.
Equipment (Telescopes)	Four 8.5m telescopes or Very Large Telescope (VLT). ESO also operates four 1.8m Auxiliary Telescopes (ATs), which are used as an interferometric array (VISA). Two wide-range telescopes, VISTA (Visible and Infrared Survey Telescope for Astronomy) of 4m, and VST (VLT Survey Telescope) of 2.6m.
Description	More recent and modern ESO observatory. Its administration was combined with the La Silla administration.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects. Observatories are granted diplomatic status and tax exemption.
Funding / Contributions	Countries participating in ESO contribute a proportion of their GDP.
Total investment	EUR 700 million
Legal Representative	Dr. Massimo Tarengui
Director	Dr. Andreas Kaufer
Phone	+56 (55) 435 000
Fax	+56 (55) 435 001
Web site	http://www.eso.org/sci/facilities/lpo/

Name	G. University of Tokyo Atacama Observatory (TAO)
Location	Cerro Chajnantor at 5640m above sea level in the Parque Astronómica Atacama, 600m above Llano de Chajnantor in the Atacama Desert, 50km east of San Pedro de Atacama. The highest telescope in the world.
Region	Antofagasta Region
Associated Organizations	University of Tokyo
Countries involved	Japan
Equipment (Telescopes)	1m infrared telescope (MiniTAO) and 6.5m telescope to be installed.
Description	6.5m telescope in design. MiniTAO telescope has been installed and is operating.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects.
Funding / Contributions	University of Tokyo.
Total investment	USD 400 million
Legal Representative	Dr. Yuzuru Yoshii
Director	Dr. Yuzuru Yoshii
Phone	+81 (422) 34 5029
Fax	
Web site	www.ioa.s.u-tokyo.ac.jp/TAO/index.html

Name	H. Large Synoptic Survey Telescope (LSST)
Location	Cerro Pachón, 80km from La Serena at 2700m above sea level.
Region	Coquimbo region
Associated Organizations	LSST Corporation made up of approximately 20 private institutions, and universities.
Countries involved	United States
Equipment (Telescopes)	8.4m telescope.
Description	The LSST is a large telescope of 8.4m. Currently under construction, it will accommodate the world's largest digital camera and provide digital images of unprecedented depth and area coverage. Forseen for 2020.
Chilean Participation	Chilean representative in the Science Council. Equivalent to 10% telescope time.
Funding / Contributions	Contributions of National Science Foundation (NSF), US Department of Energy, and 20 private institutions.
Total investment	USD 450 million
Legal Representative	Dr. Chris Smtih
Director	Dr. Anthony Tyson
Phone	+1 (530) 752 3830
Fax	
Web site	www.lsst.org/

Name	I. European Extremely Large Telescope (E-ELT)
Location	Cerro Amazonas, 150km south of Antofagasta at 2800m altitude.
Region	Antofagasta Region
Associated Organizations	European Organization for Astronomical Research in the Southern Hemisphere (ESO).
Countries involved	Germany, Belgium, Denmark, Spain, Finland, France, Netherlands, Italy, Portugal, United Kingdom, Czech Republic, Sweden, and Switzerland.
Equipment (Telescopes)	30-metre-class (39.5m) segmented telescope.
Description	World's most ambitious optical telescope.
Chilean Participation	10% (and no less than 7.5%) of the telescope observation time is reserved for Chilean astronomers.
Funding / Contributions	ESO countries.
Total investment	EUR 1000 million
Legal Representative	Dr. Massimo Tarengui
Director	
Phone	+49 (89320) 06244
Fax	
Web site	www.eso.cl/e_elt.php

Radio Telescopes

Name	J. Atacama Pathfinder Experiment (APEX)
Location	Llano de Chajnantor, plateau at 5100m above sea level in the Atacama Desert, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	European Southern Observatory (ESO), Max Planck Institute for Radio Astronomy (MPIfR), Onsala Space Observatory (OSO).
Countries involved	ESO countries, Germany, Sweden.
Equipment (Telescopes)	Millimetric and submillimetric 12m diameter antenna.
Description	Started operation in 2005. Forerunner for ALMA antenna.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects.
Funding / Contributions	ESO countries and the above mentioned private consortia.
Total investment	Not published.
Legal Representative	Dr. Massimo Tarengui
Director	Dr. Andreas Kaufer
Phone	+56 (55) 448200
Fax	
Web site	www.apex-telescope.org

Name	K. Atacama Cosmology Telescope Project (ACT Project)
Location	Cerro Toco at 5400m above sea level in the Parque Astronómico Atacama, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	Princeton University, University of Pennsylvania, NASA/GSFC, University of British Columbia, NIST , Pontificia Universidad Católica de Chile , University of KwaZulu-Natal, Cardiff University, Rutgers University, University of Pittsburgh, Columbia University, Haverford College, INAOE, LLNL, NASA/JPL, University of Toronto, University of Cape Town, University of Massachusetts and York College, CUNY.
Countries involved	United States, Spain, United Kingdom, Canada, Chile.
Equipment (Telescopes)	6m telescope.
Description	Radio observatory for CBM (Cosmic Microwave Background Radiation) studies.
Chilean Participation	Pontificia Universidad Católica de Chile (PUC). 10% of observation time is reserved for Chilean scientists.
Funding / Contributions	NSF
Total investment	USD 100 million
Legal Representative	Dr. Lyman Page
Director	Dr. Lyman Page
Phone	609-258-4400
Fax	609-258-1124
Web site	www.physics.princeton.edu/act/

Name	L. Atacama Submillimeter Telescope Experiment (ASTE)
Location	Llano de Chajnantor, plateau at 5100m above sea level in the Atacama Desert, 50km east of San Pedro de Atacama, Pampa La Bola sector.
Region	Antofagasta Region
Associated Organizations	National Astronomical Observatory of Japan (NAOJ) operates the telescope, Japanese universities from Tokyo, Nagoya, Osaka, Ibagari and Kobe, Universidad de Chile.
Countries involved	Japan, Chile.
Equipment (Telescopes)	10m submillimeter antenna.
Description	Operates at a frequency of 350 and 900 Ghz. Was used as a prototype for the ALMA construction.
Chilean Participation	Universidad de Chile and Universidad de Concepción. 10% of observation time is reserved for Chilean scientists.
Funding / Contributions	NAOJ, JAPAN
Total investment	Not published.
Legal Representative	Dr. Tetsuo Hasegawa
Director	Dr. Kotaro Kohno
Phone	
Fax	
Web site	www.ioa.s.u-tokyo.ac.jp/~kkohno/ASTE

Name	M. NANTEN2 Project
Location	Llano de Chajnantor, plateau at 5100m above sea level in the Atacama Desert, 50 km east of San Pedro de Atacama, Pampa La Bola sector.
Region	Antofagasta Region
Associated Organizations	Nagoya University, KOSMA (Cologne University), Argelander Institute (Bonn University), ETH Zurich, Radio Astronomic Observatory Seoul (Seoul National University), Universidad de Chile, University of New South Wales.
Countries involved	Japan, Germany, Australia, Switzerland, Chile, South Korea.
Equipment (Telescopes)	4m submillimeter antenna.
Description	Operates at frequencies between 115 and 880 Ghz. Originally located at Las Campanas observatory.
Chilean Participation	Universidad de Chile. 10% of observation time is reserved for Chilean scientists.
Funding / Contributions	Associated organizations.
Total investment	Not published.
Legal Representative	Dr. Yasuo Fukui (Nagoya), Dr. Jürgen Stutzki (Universität zu Köln), Frank Bertoldi (Bonn University)
Director	Dr. Yasuo Fukui, Dr. Hiroaki Yamamoto
Phone	
Fax	
Web site	http://www.astro.uni-koeln.de/nanten2/

Name	N. Atacama Large Millimeter / Submillimeter Array (ALMA)
Location	Cerro Chajnantor, plateau at 5100m above sea level in the Atacama Desert, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	National Radio Astronomy Observatory (NRAO), European Southern Observatory (ESO), National Astronomical Observatory of Japan (NAOJ).
Countries involved	United States, ESO countries, and Japan.
Equipment (Telescopes)	66 submillimeter antennas.
Description	When ALMA is fully implemented by 2013, it will be the world's largest radio observatory.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects.
Funding / Contributions	United States (NSF), Japan (NINS), ESO countries.
Total investment	USD 1000 million
Legal Representatives	Dr. Massimo Tarengui (ESO) Dr. Tetsuo Hasegawa (NAOJ) Dr. Eduardo Hardy (AUI/NRAO)
Director	Dr. Thijs de Graauw (Joint ALMA Observatory Director)
Phone	+56 (02) 467 6100 +56 (02) 755 0107
Fax	
Web site	www.almaobservatory.org

Name	O. Polarbear
Location	Cerro Toco at 5200m above sea level in the Parque Astronómico Atacama, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	University of California at Berkeley, Lawrence Berkeley National Lab, University of Colorado at Boulder, University of California at San Diego, Laboratoire Astroparticule & Cosmologie, Imperial College, KEK, McGill University, Cardiff University.
Countries involved	United States, Canada, United Kingdom, France, and Japan,
Equipment (Telescopes)	3.5 m Huan Tran Telescope (HTT). Attached to the telescope is the POLARBEAR experiment, which is an array of bolometers cooled to less than 1K (-458°F).
Description	POLARBEAR is a Cosmic Microwave Background experiment using a large imaging camera and the dedicated Huan Tran Telescope. Ploarbear-I was deployed at the end of 2011 and achieved first light in Chile on January 10th, 2012 with observations of Saturn. Polarbear-II is expected to be deployed in 2014.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects.
Funding / Contributions	NSF; Department of Energy, Office of High Energy Physics; NSERC; Science and Technology Facilities Council, European Union Marie Curie; Miller Institute for Basic Research in Science, James B Ax Family Foundation.
Total investment	USD 8.4 million
Legal Representative	
Director	Dr. Adrian Lee

Director	
Phone	
Fax	
Web site	http://bolo.berkeley.edu/polarbear/

Name	P. Cornell Caltech Atacama Telescope (CCAT)
Location	Cerro Chajnantor at 5612m above sea level in the Parque Astronómico Atacama, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	The CCAT consortium includes Cornell University, California Institute of Technology with the Jet Propulsion Laboratory, University of Colorado, University of British Columbia for a Canadian university consortium, the UK Astronomy Technology Centre on behalf of the United Kingdom, and Universities of Cologne and Bonn.
Countries involved	United States, Canada, United Kingdom, Germany.
Equipment (Telescopes)	25m submillimeter antenna.
Description	Giant radio telescope which is planned to make use of the new generation of bolometric detectors which revolutionize fast mapping in submillimetric wavelengths. To be installed.
Chilean Participation	10% of the telescope observation time will be reserved for Chilean scientists.
Funding / Contributions	Associated organizations.
Total investment	USD 110 million
Legal Representative	Dr. Eduardo Hardy (AUI / NRAO)
Director	Dr. Riccardo Giovanelli
Phone	607-255-6505
Fax	
Web site	www.submm.org/tech.html

Name	Q. Cosmology Large Angular Scale Surveyor (CLASS)
Location	Cerro Toco at 5200m above sea level in the Parque Astronómico Atacama, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	Johns Hopkins University (JHU) in Baltimore, NASA Goddard Space Flight Center in Greenbelt
Countries involved	United States
Equipment (Telescopes)	Survey telescope
Description	CLASS is expected to search the microwave sky for a unique polarization pattern predicted to have arisen in the infant universe. The telescope is will be completed in 2014.
Chilean Participation	10% of the telescope observation time is reserved for Chilean projects.
Funding / Contributions	NSF (USD 5 million), Johns Hopkins University
Total investment	USD 7 million
Legal Representative	
Director	Dr. Charles Bennett

Name	R. Chajnantor Observatory (1998 – 2008)
Location	Chajnantor plateau at 5100m above sea level in the Atacama Desert, 50 km east of San Pedro de Atacama.
Region	Antofagasta Region
Associated Organizations	California Institute of Technology (Caltech), Universidad de Chile and Universidad de Concepción
Countries involved	United States, Chile.
Equipment (Telescopes)	Interferometer of 13 elements.
Description	Radio observatory for CBM (Cosmic Microwave Background Radiation) study.
Chilean Participation	Universidad de Chile and Universidad de Concepción. 10% of observation time is reserved for Chilean scientists.
Funding / Contributions	National Science Foundation (NSF), California Institute of Technology (Caltech), Maxine and Ronald Linde, Cecil and Sally Drinkward, Barbara and Stanley Rawn Jr., Rochus Vogt, Kavli Institute, Canadian Institute for Advanced Research.
Total investment	No information available.
Legal Representative	
Director	Dr. Anthony C.S. Readhead
Phone	(626) 395 4972
Fax	(626) 568 9352
Web site	http://chajnantor.caltech.edu/

APPENDIX G

Foreing Investment in International Observatories

	Cost (million USD)
Operating	1140
Magellan Telescopes	100
Gemini	300
VLT	700
ACT*	40
Under construction	1000
ALMA	1000
Polar Bear*	8.2
Planned	3100
TAO*	100
LSST	500
CCAT*	200
GMT	800
E-ELT	1500

*Parque Astronómico Atacama

APPENDIX H

Astronomy Funding 2006–2011

	Thousand USD / yr.**						
	2006	2007	2008	2009	2010	2011	TOTAL
CONICYT	2,027	1,811	4,720	4,216	5,384	5,693	23,850
Astronomy Program	517	155	886	1,048	1,402	1,163	5,171
Concurso ALMA	517	32	545	687	929	536	3,246
Postdoc ALMA	–	–	–	–	–	60	60
Concurso GEMINI	–	118	305	328	436	528	1,714
Postdoc GEMINI	–	6	35	34	37	39	151
Fondecyt	378	461	746	909	1,112	1,430	5,037
Postdoc	46	73	178	192	225	441	1,155
Regulares	321	374	534	597	686	765	3,277
Iniciación	11	15	34	120	201	225	605
PIA	–	–	1,893	1,144	1,646	1,841	6,524
Anillos	–	–	–	–	294	310	604
Basal	–	–	1,893	1,144	1,352	1,531	5,920
Fondap	1,132	1,195	1,195	1,114	1,223	1,259	7,118
Iniciativa Científica Milenio (ICM)*	–	–	374	459	397	1,068	2,298
Operación	–	–	345	425	343	937	2,050
Proyección al Medio Externo (PME)	–	–	29	34	29	99	192
Redes Formales de Colaboración	–	–	–	–	25	31	56
TOTAL	2,027	1,811	5,094	4,675	5,781	6,760	26,148

* Transferred funds.

** Nominal pesos converted at observed exchange rate per year (Source: Chilean Central Bank).

	2006	2007	2008	2009	2010	2011	TOTAL
			Thousand pesos / yr.				
CONICYT	1,074,824	946,558	2,462,810	2,359,319	2,747,617	2,751,675	12,342,803
Astronomy Program	274,189	81,014	462,116	586,808	715,702	561,932	2,681,761
Concurso ALMA	274,189	16,560	284,614	384,518	474,156	259,141	1,693,178
Postdoc ALMA	–	–	–	–	–	28,875	28,875
Concurso GEMINI		61,493	159,087	183,326	222,737	255,107	881,750
Postdoc GEMINI		2,961	18,415	18,964	18,809	18,809	77,958
Fondecyt	200,635	241,144	389,198	509,001	567,515	691,063	2,598,556
Postdoc	24,490	37,932	93,000	107,634	114,950	212,944	590,950
Regulares	170,111	195,407	278,708	334,187	350,171	369,549	1,698,133
Iniciación	6,034	7,805	17,490	67,180	102,394	108,570	309,473
PIA	–	–	987,986	640,000	840,000	890,000	3,357,986
Anillos	–	–	–	–	150,000	150,000	300,000
Basal	–	–	987,986	640,000	690,000	740,000	3,057,986
Fondap	600,000	624,400	623,510	623,510	624,400	608,680	3,704,500
Iniciativa Científica Milenio (ICM)*	–	–	195,270	256,981	202,726	516,063	1,171,039
Operación			180,000	237,821	175,000	453,000	1,045,821
Proyección al Medio Externo (PME)			15,270	19,160	14,976	48,063	97,469
Redes Formales de Colaboración			–	–	12,750	15,000	27,750
TOTAL	1,074,824	946,558	2,658,080	2,616,300	2,950,343	3,267,738	13,513,842

* Recursos transferidos

APPENDIX I

International Astronomical Instrument Development Centers

The following is a limited number of some of the known international centers that are actively participating in the development of astronomical instruments:

Herzberg Institute for Astrophysics (HIA), Canada

Advanced Technology Center (NAOJ), Japan

Max Plank Institute for Astronomy, Germany

Center for Adaptive Optics (University of California at Santa Cruz), USA

University of Arizona (Steward Observatory, College of Optical Sciences, Mirror Lab), USA

The Istituto Nazionale di Astrofisica (INAF), the Arcetri Astrophysical Observatory, Italy and Microgate Engineering, Italy

NRAO New Technology Center Charlottesville, USA

Group for Advanced Receiver Development (GARD) and Physical Electronic Laboratory (MC2) – Chalmers University, Sweden

STFC Rutherford Appleton Laboratory (RAL), UK

Yebes Astronomy Center, Spain

Harvard Smithsonian Center for Astrophysics (CfA), USA

University of Cologne, Germany

Leiden Observatory (Astronomical Instrumentation), The Netherlands

Laboratoire d'Astrophysique, Observatoire de Grenoble, France

The UK Astronomy Technology Centre (STFC), UK

APPENDIX J

International Consultants for the Roadmap

Dr. Gary H. Sanders

A. Curriculum Vitae

Education:

A.B. degree, 1967, Columbia University, physics major
Ph.D., 1971, M.I.T., high-energy physics
Thesis advisor: Sam Ting
Thesis topic: Photoproduction of ro mesons on complex nuclei

Employment and Special Assignments:

Postdoctoral fellow, 1971-1972, Princeton University Physics Department
Assistant Professor, 1972-1978, Princeton University Physics Department
Technical Staff Member, Los Alamos National Laboratory, 1978-1994
Los Alamos Meson Physics Facility (LAMPF), 1978-1989
Office of the Associate Director for Physics and Mathematics, 1983-84
Office of the Associate Director for Research, 1989 - 1994
Team Leader, Human Studies Project Team, 1994
Principal Investigator and Program Manager for High Energy Physics, 1990-1994

Project Manager and Department Head, GEM Detector Dept. Superconducting Super Collider Laboratory, 1992-1993.

Project Manager and Deputy Director, Laser Interferometer Gravitational Wave Observatory, California Institute of Technology, 1994 - 2004.

Principle Investigator, Project Science: Education and Training in the Management of Big Science Projects, Workshop series supported by the US National Science Foundation. 2001 - present.
Project Manager, Thirty Meter Telescope Project, California Institute of Technology and the University of California, TMT Observatory Corporation, 2004 - present.

Faculty Associate, Division of Physics, Mathematics and Astronomy, California Institute of Technology, 2005 - 2007.

Research:

High-energy physics, tests of QED and vector meson physics (DESY, Hamburg), hyperon beta decay (BNL), Drell-Yan physics and J/Y physics (FNAL), rare muon decays (LAMPF), rare kaon decays (BNL), neutrino physics (LAMPF), physics at colliders (LEP/CERN and SSC), experimental gravitational waves (LIGO), management of large science projects.

Author or coauthor of 170 published journal or scientific articles. List available on request.

Scientific Community Service and Consultation:

Service on US Department of Energy reviews (Lehman reviews) of high energy physics experiments (CDF, D0, HEPAP subpanel on Long Baseline Neutrino Experiments).

Facilities, Security and Safeguards External Advisory Board, Los Alamos National Laboratory (1996)
Lecturer, Management School La conduite de projets à l'IN2P3, CNRS, La Londe, France, 1996, 1997, 1998.

External Advisory Board, Cold Dark Matter Search II, UC Berkeley, 1997– 2005.
Chair/Member, Millimeter Array (ALMA) Oversight Committee, US National Science Foundation, 1997 – 2005.

Chair, Director's Reviews of NuMI, Fermi National Accelerator Laboratory, 1998.
University of California Office of the President Review of the National Ignition Facility, Lawrence Livermore National Laboratory (1999).

Borexino Review Panel, US National Science Foundation, 1999 – 2002.

National Ecological Observatory Network Management Panel, US National Science Foundation, 2000.

Rare Symmetry Violating Processes Cost Review Panel, US National Science Foundation, 2000.

Chair, Rare Symmetry Violating Processes Oversight Panel, US National Science Foundation, 2000 – 2002.

Chair/Member, Atacama Large Millimeter Array Management Advisory Committee, US National Science Foundation and European Southern Observatory, 2001 – 2006.

Panelist, NSF Management Organization Roundtable, "U.S. Astronomy and Astrophysics: Managing an Integrated Program (2001)", Committee on the Organization and Management of Research in Astronomy and Astrophysics, National Research Council, Space Studies Board, June 2001.

Chair, Management Review of Associated Universities, Inc., US National Science Foundation, 2002.
George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Consortium Development Project First Year Review Panel, US National Science Foundation, 2002.

Advisory Committee for the NSF Directorate for Mathematical and Physical Sciences (MPS), US National Science Foundation, appointed October 2002 – September 2005.

Search Committee for a Deputy Director, Large Facility Projects, NSF Office of Budget, Finance, and Award Management, US National Science Foundation, 2002

Reviewer of the California Extremely Large Telescope (CELT), University of California Office of the President, 2002.

Red Team reviewer, AURA proposal to NSF for the Thirty Meter Telescope development, 2003.

Red Team reviewer, Large Synoptic Survey Telescope proposal to NSF, 2003.

Baseline Review, IceCube, US National Science Foundation, 2004.

Chair, Subpanel on Projects, Committee of Visitors, Office of High Energy Physics, US Department of Energy, 2004.

Technical Advisory Board, HYTEC Inc., Los Alamos NM, 2004.

Research Participant, Facilities Subcommittee, Business and Operations Advisory Committee, National Science Foundation, 2005.

Member, National Research Council Study Committee, Assessing the Results of External Independent Reviews for U.S. Department of Energy Projects, 2006.

Consultant and Speaker, ATLAS Management Outing, European Organization for Nuclear Research (CERN), Chateau d'Oex, Switzerland, 2006.

Consultant, National Center for Supercomputer Applications, Petascale Project, 2006 – present.
Project Manager Search Committee, National Ecological Observatory Network, NEON, Inc., 2006.
Chair, National Ecological Observatory Network (NEON) Conceptual Design Site Visit, US National Science Foundation, November 2006.

Consultant, BBN Technologies Corp., Cambridge, MA, Global Environment for Networking Innovations (GENI) Project, US National Science Foundation, 2006.

Member, Deep Underground Science and Engineering Laboratory (DUSEL) Solicitation 3 (S3) Site Selection Review Panel, US National Science Foundation, February – May 2007.

Consultant/lecturer, Management of Big Science, Argonne National Laboratory, 2007.

Management Advisory Board, Global Environment for Network Innovations (GENI) Project, BBN Technology, 2007 – 2008.

Panel Member, International Review of Research and Academic Activities at the National Astronomical Observatory of Japan (NAOJ), Optical and Infrared Astronomy Division, Mitaka, Japan, 2008.

Assessor, European Science Foundation, Physical and Engineering Sciences, 2008.

Community Service and Recognition:

Board Member, Los Alamos Montessori School, 1981–1990.

Board Member, New Mexico Citizens for Clean Air and Water, 1981 – 1994.

State Chairman, New Mexico Conservation Voters Alliance, 1982 – 1990.

Chairman, Water Task Force, Governor's Office, State of New Mexico, 1982 – 1983.

Listed in Who's Who in America, 56th and 57th Edition.

Fellow, World Innovation Foundation.

Member, American Association for the Advancement of Science.

Member, International Society for Optical Engineering (SPIE).

Full member, American Astronomical Society.

Fellow, American Physical Society, appointed 2003. Appointment citation:

> *For his remarkable abilities to synthesize all the elements of large, complex, subtle experiments, and for his leadership and cultivation of the communities such experiments require.*

Nominated by: APS

S. Publications

(w/H. Alvensleben et al.) “Validity of Quantum Electrodynamics at Extremely Small Distances,” Phys. Rev. Lett. 21, 1501 (1968).

(w/H. Alvensleben et al.) “Validity of Quantum Electrodynamics at Extremely Small Distances,” Proceedings of the XIV International Conference on High Energy Physics, Vienna, Austria (September 1968) no. 958.

(w/H. Alvensleben et al.) “Photoproduction of Charged Pion Pairs on Protons,” Phys. Rev. Lett. 23 , 1058 (1969).

(w/H. Alvensleben et al.) “Photoproduction of Charged Pion Pairs on Protons,” Proceedings of the International Seminar, Dubna, USSR (September 1969).

(w/H. Alvensleben et al.) “Leptonic Decays of Vector Mesons: The Observation of Coherent Interference Pattern Between ρ,ω Decays,” Proceedings of the International Seminar, Dubna, USSR (September 1969).

(w/H. Alvensleben et al.) “On the Photoproduction of Neutral Rho Mesons from Complex Nuclei,” Proceedings of the International Seminar, Dubna, USSR (September 1969).

(w/H. Alvensleben et al.) “Photoproduction of Neutral Rho Mesons,” Nucl. Phys. B18, 333 (1970).

(w/H. Alvensleben et al.) “Photoproduction of Neutral Rho Mesons from Complex Nuclei,” Phys. Rev. Lett. 24 , 786 (1970).

(w/H. Alvensleben et al.) “Determination of Strong Interaction Nuclear Radii,” Phys. Rev. Lett. 24 , 792 (1970).

G.H. Sanders, “Photoproduction of ρo Mesons on Complex Nuclei, “Herbstschule fuer Hochenergiephysik, Maria Laach, Germany (September 1970).

(w/H. Alvensleben et al.) “ Interference in $\varpi+\varpi-$ Photoproduction,” XV International Conference on High Energy Physics, Kiev, USSR (September 1970).

(w/H. Alvensleben et al.) “Photoproduction of Massive Pion Pairs,” XV International Conference on High Energy Physics, Kiev, USSR (September 1970).

(w/H. Alvensleben et al.) “Determination of the Photoproduction Phase of ρ o Mesons,” Phys. Rev. Lett. 25, 1377 (1970).

(w/H. Alvensleben et al.) “Observation of Coherent Interference Pattern Between ρ and ω Decays,” Phys. Rev. Lett. 25, 1373 (1970).

(w/H. Alvensleben et al.) “Determination of the Photoproduction Phase of ρo Mesons,” Nucl. Phys. B25, 342 (1971).

(w/H. Alvensleben et al.) “Observation of Coherent Interference Pattern Between ρ,ω Decays,” Nucl. Phys. B25, 333 (1971).

(w/H. Alvensleben et al.) “Photoproduction of Pion Pairs with High Invariant Mass,” Phys. Rev. Lett. 26, 273 (1971).

(w/H. Alvensleben et al.) "Precise Determination of ρ,ω Interference Parameters from Photoproduction of Vector Mesons Off Nucleon and Nuclei," Phys. Rev. Lett. 27, 888 (1971).

(w/H. Alvensleben et al.) "Determination of the Photoproduction Phase of ϕ Mesons," Phys. Rev. Lett. 27, 444 (1971).

(w/H. Alvensleben et al.) "Photoproduction and Forbidden Decays of ϕ Mesons," Phys. Rev. Lett. 28, 66 (1972).

(w/K.J. Anderson et al.) "Mu-Pair Production by 150 GeV/c Hadrons," Invited paper 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford University, August 1975.
(w/K.J. Anderson et al.) "Dimuon Production by ϖ+ and Protons with a Large Acceptance Spectrometer," 1975 Annual Meeting of the Division of Particles and Fields, Am. Phys. Soc., University of Washington, Seattle, WA, August 1975.

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TMT Status Report, Jerry Nelson and Gary H. Sanders, SPIE 6267-60, SPIE Astronomical Telescopes and Instrumentation, Orlando, FL, May 2006 (TMT.PMO.JOU.06.001.REL01)

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Harry Collins and Gary Sanders, "They Give You the Keys and Say 'Drive It'; Managers, referred expertise, and other expertises.", Studies in History and Philosophy of Science Part A, Volume 38, Issue 4, Pages 621-641 (December 2007)

Dr. Angel C. Otárola Medel

A. Curriculum Vitae

Summary of qualifications:

Civil Engineer with specialty in Geography. Undergraduate studies carried out at the Universidad de Santiago (Chile) from 1982 to 1989. Received a diploma on Computer Sciences (relational databases, operative systems and microprocessors) from Universidad Católica del Norte (Chile). Was awarded a Master of Science in the field of Atmospheric Sciences with a research on the modeling of the Relative Permittivity of Liquid Water at frequencies from microwaves up to 1.5 THz in May 2006. In December 2008 was awarded a Ph.D. degree in Atmospheric Sciences with minor in Planetary Sciences with a research on The Effects of Turbulence in an Absorbing Atmosphere on the Propagation of Microwave Signals Used in an Active Sounding System. All graduate education performed at the University of Arizona (USA) under the supervision of Prof. Dr. E. R. Kursinski.

Education:

2004 - 2008:
University of Arizona (Tucson, AZ, USA), M.S. and Ph.D. in Atmospheric Sciences with minor in Planetary Sciences.

1992 - 1992:
Universidad Católica del Norte (Antofagasta, Chile), Diploma on Computer Sciences.

1982 - 1989:
Universidad de Santiago de Chile (Santiago, Chile), B. of Engineering.

Employment:

2007 - Present: Thirty Meter Telescope Corporation

Current Job Title: Senior Scientist

Perform studies on the effects of atmospheric processes on the propagation of radiation from astronomical sources. Specifically, for the modeling of water vapor absorption and aberration of the astronomical signal wavefronts due to atmospheric turbulence. Results of this research have been presented in the peer review literature and conference proceedings. Collaborates with the TMT's Adaptive Optics group in the study of the performance of Lasers (at 589 nm) in their interaction with the mesospheric sodium (Na) Layer as a way to create a Laser Guide Star System for TMT's adaptive optics.

In a previous assignment, represented the interest of the TMT Observatory Corporation before the government of Chile and the Chilean astronomy community to create the necessary conditions for the possible construction of the Thirty Meter Telescope at the summit of the Cerro Armazones in the Region of Antofagasta (Chile). Was also involved in the study of the magnitude and variability of the integrated water vapor in the atmospheric column at all the sites of interest for the deployment of TMT. Atmospheric water vapor is one of the most relevant absorbing gases of electromagnetic radiation from the near- to far-infrared limiting this way the capabilities of optical/infrared observatories to study the universe at these spectral windows.

2004 – 2008: University of Arizona
Position: Graduate Student (Research Assistant)

In the course of his graduate education (M.S. and Ph.D.) he conducted research on the propagation of microwaves and millimeter-waves through clouds and also through turbulent and absorbing medium, such as is typically found in planetary atmospheres (specially the Earth's atmosphere). In the propagation of electromagnetic signals through clouds (which consists of suspended water drops), the relevant parameter is the relative permittivity of pure liquid water. This is a complex quantity that varies with the temperature of the liquid water and is a strong function of the frequency of the radiation propagating through the liquid medium. This quantity is of great importance in the performance of a new active sounding system instrument for the Earth's atmosphere, the Active, Temperature, Ozone, and Moisture Microwave Spectrometer (ATOMMS), and consequently a research of the liquid water relative permittivity was required. Existing models for the determination of the liquid water relative permittivity are of limited frequency range applicability or have some limited application in the temperature range of the liquid water. Consequently, for a M.S. research a review of the scientific literature was conducted to compile a large set of laboratory measurements of the complex relative permittivity of liquid water as a function of temperature and frequency of the radiation propagating through the medium. This data, together with the application of inverse theory, was used to derive a new -two relaxations- model for the determination of this physical quantity in the frequency range from microwaves up to 1.5 THz and for a temperature range found in clouds in the Earth's atmosphere (from slightly super-cooled water up to +30 Celsius degrees).

ATOMMS is an instrument designed to probe the atmosphere by means of a technique called Radio Occultation. An active system like this allows the determination of the atmospheric thermodynamic quantities (temperature and pressure), as well as the concentration of gases of interest (water vapor, ozone, etc.) by monitoring the time-delay and the absorption experienced by an electromagnetic signal (or several) at selected frequencies when propagating through the limb of the atmosphere from satellite-to-satellite. In a system like this is very important to understand and correct for the amplitude fluctuations that the signal might experience, when traversing the atmosphere, induced by any source other than the absorption of energy by the concentration of the absorbing gas of interest. One of the sources of error is due to random amplitude fluctuations induced by atmospheric turbulence. For a Ph.D. a research was conducted that leaded to find a general mathematical model to estimate the amplitude fluctuations an electromagnetic signal would experience when traversing a turbulent and absorbing medium. i.e. the model incorporates the random fluctuations, due to turbulence, in the real and imaginary components of the gaseous atmosphere's index of refraction.

2001 – 2004: European Southern Observatory appointed at the National Radio Astronomy Observatory of the USA (Based in Tucson, AZ, USA)
Job position: Test Engineer

While at this position he was a member of the ALMA Antenna Evaluation Group and helped devise procedures and tests for he verification of technical specifications of two ALMA prototype antennas (radio telescopes). Both prototypes were designed and built to meet the technical standards and specifications needed for the observation of the universe at millimeter and sub-millimeter wavelengths. The technical specifications covered the following aspects: quality of the primary reflector surface, pointing and tracking of the antenna at varying wind and thermal loads, mechanical path-length stability as a function of temperature, as well as the verification of the ability of the antenna panels to diffuse the visible, near and mid-infrared radiation as to allow solar observations at the same time that protects the optical systems and the structures near the primary focus of the antenna.

Specific tasks included:

Implementation of a weather station for the continuous monitoring of the atmospheric conditions at the ALMA Test Facility (VLA site, NM). This included designing the mechanical interfaces, setup the electronic interface of all equipments, programming of data acquisition software (under Python environment) and of tools for data visualization and query of the weather variables database. The instruments included, a CR4 Chilled Mirror Hygrometer, Sonic Anemometer, Solar Flux meters, and additional propellers wind anemometers.

Devising solutions for the mechanical interfacing of monitoring equipment to the prototype antennas with the goal of studying the mechanical response of the antenna to wind and thermal loads. The equipment used in these tests included: Laser ranging devices of the model API-5D (Automated Precision, Inc), Laser Quadrant Detectors (Fixtur-Laser), Model 86 uni-axial Accelerometers (Endevco, Inc), and PT100 model high accuracy and high resolution temperature sensors.

Performed pre-analysis in the time and frequency domain of the data obtained from the tests.

1996 - 2001: European Southern Observatory (Antofagasta, Chile)
Job position: Site Tester

While holding this position explored the Atacama Desert region to identify places suitable for the deployment of a large radio-astronomy interferometer to be operated at millimeter and sub-millimeter wavelengths. Helped planning the logistics, business and contracts with providers for the development of the sites under study. Helped deploying and operating specialized instruments for the continuous monitoring of relevant atmospheric parameters at these sites. In particular, a relevant variable under study it was the magnitude and variability of water vapor in the atmospheric column. Water vapor absorbs presents a permanent dipole and consequently exhibits strong rotational absorption lines in the millimeter and sub-millimeter part of the electromagnetic spectrum limiting this way the capabilities of a radio interferometer operating at these wavelengths. In the course of this assignment collaborated in the setup of instruments, operations as well as in the data analysis and publications of results with an international team of engineers and scientists from several scientific organizations, such as: European Southern Observatory, the Nobeyama Radio Observatory (Japan), National Radio Astronomy Observatory (USA), Princeton University/ Pennsylvania State University (USA), California Institute of Technology (USA), Universidad de Chile, and the Harvard-Smithsonian Center for Astrophysics (USA).

As part of this collaboration effort, also assisted with the logistics, assembly and setup of the Cosmic Background Imager (Caltech), the Mobile Anisotropy Telescope (MAT 1 & 2, Princeton/Pennsylvania), and the Small Radio Telescope (SRT, Harvard-Smithsonian Center for Astrophysics).

1990 - 1996: European Southern Observatory (La Silla Observatory, Chile)
Job position: Radio-Telescope Operator

At this position assisted the visiting astronomers in the operation of the Swedish-ESO Submillimetre Telescope (SEST). This included assistance with the setup of heterodyne receivers and bolometers operating at millimeter and sub-millimeter wavelengths. Also, helped programing some added capabilities to the online data reduction software for the quick analysis of single-dish radio astronomical data. Participated in the regular calibration and setup of all receivers. Also, designed and built an automated system for the adjustment of the SEST antenna surface after holography measurements.

1989 – 1990: Terrasat S.A. (Santiago, Chile)
Job position: Consulting Engineer

Conducted geodetic survey to support mining claims. Designed and programmed software for data analysis of geodetic measurements. Specifically, programmed algorithms for the transformation of coordinates (datum, and for transformation between different data formats).

1989 – 1991: Universidad de Santiago de Chile (Santiago, Chile)
Department of Geography, College of Engineering
Part-time instructor of the class of Topography.

Training:

1995 Fundamental of UNIX Operative System, HP, Atlanta, GA, USA.
ANSI C Programming, HP, Atlanta, GA, USA.
1997 Kalman Filtering, Navtech Seminars, San Diego, CA, USA.
1998 Summer School on Millimeter Interferometry, IRAM, Grenoble, France.
2007 Asian Radio Astronomy Winter School, NAOJ, Tokyo, Japan.
2010 Adaptive Optics Summer School, University Of California at Santa Cruz.

Memberships:

Dr. Otárola is a regular member of the Institute of Electrical and Electronics Engineers (IEEE), the American Geophysical Union (AGU), American Meteorological Society (AMS) and the Optical Society of America (OSA).

T. Publications
Journal Papers

Kursinski, E. R., Ward, D., Stovern, M., Otárola, A.C., Young, A., Wheelwright, B., Stickney, R., Albanna, S., Duffy, B., Groppi, C., and Hainsworth, J. (2011: Accepted for publication),"Development and testing of the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) cm and mm wavelength occultation instrument", Atmospheric Measurement Techniques (AMT)a, Special Issue: Observing atmosphere and climate with occultation techniques – results from the OPAC 2010 Workshop.

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Conference Proceedings

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Otárola, A.C., Querel, R. and Kerber, F. (2011), "Precipitable Water Vapor: Considerations on the water vapor scale height, dry bias of the radiosonde humidity sensors, and spatial and temporal variability of the humidity field", arXiv:1103.3025v1 [astro-ph.IM], Contribution in conference "Comprehensive characterization of astronomical sites", held October 4-10, 2010, in Kislovodsk, Russia.

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