APEX beyond 2016 - The Evolution of an Experiment into an efficient and productive Submillimeter Wavelength Observatory

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ABSTRACT

The Atacama Pathfinder EXperiment (APEX) operates a 12m submillimeter wavelength telescope in the high Andes in Chile at 5107 m above sea level since 2006[1]. Several steps have been taken to improve the operation efficiency of the facility in the given harsh environmental conditions[2]. The developments in remote control and -sensing allowed for the transition to a remote science operations scheme, observing 24/7 from the basecamp control center in San Pedro de Atacama in 2017. Also engineering and maintenance is in the transition phase to a similar scheme to minimize presence and activities at the very high site. Instrument control servers allowing remote operation even of heterodyne THz instrumentation, with no compromise on instrument performance, had been developed and proven to reliably work[3]. The transition to full remote science operations required major hardware upgrades on the antenna drive system and a failsafe remote-control system to ensure the safety of the antenna, the Sun Avoidance System (SAS). We report on the layout, the implementation and on the experience of the first year of this new operations model starting in April 2017.

The engineering tasks also are in a transition phase to a scheme that minimizes the presence at the antenna. Daily engineering work at the high site for preventive and corrective maintenance can be reduced when all critical hardware systems are integrated in a remote monitoring and control system. We have started with this in 2015 and have stepwise introduced this new scheme. This required the introduction of redundancies of systems as well as the extension of sensing points and remote-control interfaces, throughout all levels in the project breakdown structure of the telescope and its auxiliary systems. We present examples of theses implemented systems and discuss the concept of redundancies.

The APEX observatory is the smallest ESO site in Chile, incorporated as a department of LPO, the ESO La Silla – Paranal Observatory, within the directorate of Operations (DoO). The work presented will attempt an outline of approaches that can be applied to telescopes exposed to similar environmental conditions as well as to larger and distributed operations such as envisaged for the Paranal Observatory extended by the ELT on Cerro Armazones.

Keywords: Submillimeter Telescopes, Remote Operation, THz Frequency Astronomy

1. INTRODUCTION

The APEX telescope is located at the high plateau at the foot of the Chajnantor summit (see Figure 1), at coordinates 23°00'20.91"S, 67°45'32.95"W in the Chajnantor high plateau. The site can be reached by car from the APEX base station which is located in San Pedro de Atacama, approximately 68 km away from the telescope, whereas 2/3 of the way is in dirt road conditions. At the high site, operations take place at the telescope as well as at the locations indicated in Figure 1. The orange track shows a dirt track that reaches a small hill called "Cerro Chico" at whose summit we operate a radiofrequency network link that connects the high site to the base station in San Pedro de Atacama for data transfer and communication, via a direct line of sight distance of 45.5 km. How we centralized these distributed operations from a remote-control room in the base station in San Pedro is described in the following sections.

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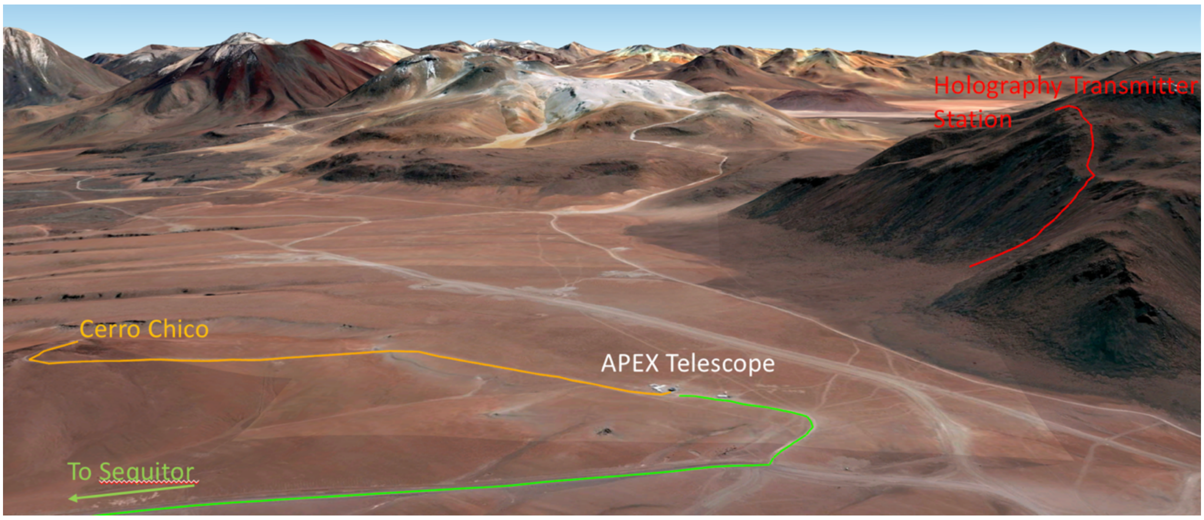

Figure 1: APEX Chajnantor Operations at the High Site. The orange path indicates a dirt road from the telescope to Cerro Chico, where the radio link to the base station in San Pedro is located. The green path indicates the road to the base station in San Pedro de Atacama at 68km distance. The hiking path to the holography transmitter station is indicated in red. Please see further explanations in the text.

2. SCIENCE OPERATIONS

Given the multi-partner nature[1] of the APEX project there are four different queues to receive observing proposals from Principal Investigators (PIs). Each of them follows the rules and deadlines established by the host institution, but there are always two half-yearly calls. Such proposals are evaluated based on scientific merit and technical feasibility by the Time Allocation Committees from the different partner institutions. The fraction of them obtaining telescope time are executed yearly within the period between mid-March and end of December, the so-called science operations period. During the remaining lapse between January and mid-March weather conditions are adverse for sub-mm observations (high humidity and frequent precipitation) over the Chajnantor plateau, therefore no observations are scheduled. Instead, this yearly shutdown period is used for maintenance and upgrades of telescope systems, instrumentation and auxiliary systems. These periods are illustrated in Figure 2 .

The observatory offers a suite of facility instrumentation, available to all partners. These are versatile instruments that can be used to address a large variety of scientific projects and produce with 78% the main fraction of the scientific publications resulting from APEX observations. These instruments are operated and maintained by the observatory staff. In addition, the partners bring PI instruments with more specific capabilities or more experimental technology. Some of these instruments are permanently installed at the telescope and used during the partner's time, serving their specific community. These are often also offered to researchers from other partners under certain agreements. Finally, APEX also has space to host visiting instruments (in PI mode) which are installed and used temporarily to address specific research programs not possible with other permanent instrumentation or for testing experimental capabilities or observing modes.

The observing schedule is split in observing blocks, one to few weeks long, each assigned to a specific partner. The distribution and duration of these blocks are planned in accordance to the share of each partner in the project and 10% of the observing time is available to researchers from Chilean institutions. In each block the pool of science projects from the partner is executed in service mode, attending to project ranking, sources visibility, weather requirements and instrument availability. The partners can also use their observing blocks to install or commission PI instrumentation. A maximum of 10% of the yearly available observing time is dedicated to technical activities for the facility and this is scheduled in small periods between science observing blocks. Technical time is used to perform engineering tasks, maintenance activities and technical observations like on sky calibrations, holography measurements to evaluate or improve the dish surface accuracy, refinements of telescope pointing models, etc. Some of these technical observations are also flexibly scheduled during the science blocks whenever observing conditions are suitable to conduct them.

During the science operations period, the execution of observations is coordinated by APEX staff and conducted in collaboration with visiting astronomers from the partner institutions. Since 2010 the telescope operates around the clock, distributing the work in three 8-hours observing shifts (morning, afternoon and night). Each shift is covered by a member of the APEX science operations team and one of the visiting astronomer who oversees the detailed project scheduling of the partner's queue. Sharing the operation with rotating visiting astronomers has turned to be very beneficial for the communities that they serve. They are deeply involved in the observing process, data reduction and quality assurance, and young astronomers can gain first-hand experience in the full process. In most cases, these astronomers are highly motivated to learn and eager to apply their unique expertise in proposing own research projects to the corresponding queues.

The APEX science operations team is composed by 10 ESO staff members working in bi-weekly shifts (one week at the observatory, one week off). The team comprises 4 astronomer positions, including the group head, and 6 telescope and instrument operator positions (TiO). They are responsible for efficiently operating the antenna and instrumentation when executing the queue of science projects and for producing the initial data quality assurance of the collected data. They also monitor all systems to identify imminent or potential problems affecting the operation.

APEX astronomers lead the monitoring and calibration plans for the different antenna subsystems and instrumentation. They work in the design of strategies to run those plans, in their implementation, the analysis of the collected data and the identification of problems define improvement proposals. They also participate regularly in the observations and supervise the development and maintenance of observing procedures, data reduction, quality control and archiving. A rotary astronomer on duty (AoD) coordinates daily operation activities, organizes technical observations and is the main point of communication with visitors and staff engineers. APEX TIOs, when not involved in the daily operation, participate in specific projects like development of operational tools, analysis of technical data, documentation of procedures, etc. To ensure fluent communication and an efficient handover strategy TiOs and astronomers do not commute the same week day, which allows a better overlap between group members. In addition, there is some overlap between the incoming and outgoing astronomer who work in counter-shift, so they can exchange face-to-face information about problems or ongoing activities. Each member produces a report at the end of his shift. Group meetings are held twice a week to discuss ongoing issues, disseminate information or share results of ongoing projects.

All scientific and technical data collected during the science operations period are kept and archived in a repository at the observatory. A copy is also sent to the general archive kept at the ESO Headquarters in Germany. A network link allows to continuously transfer these data from Chile to the archive in Germany, where they are ingested into the archive. At this stage, PIs are immediately notified and can access their data via web. This fast link gives the possibility to the APEX users to provide feedback to the astronomers observing their projects with a latency of a couple of days. When data rates exceed the network link capacity, the remaining data are copied into disks which are sent via air freight to Germany and then archived. Project PIs and their teams are exclusive proprietaries of their data collected with facility instrumentation for a period of 1 to 3 years (depending on the partner). After this proprietary period, data are available to the community through the ESO archive, which enormously increases the legacy value of the project. In this sense are particularly relevant the APEX large programs: scientific projects requiring up to hundreds of hours of observing time, intended to address important questions that cannot fit within regular projects. Datasets (in raw format) observed under these programs are made public immediately when archived, and sometime later high-quality data products are made available by ESO to the community. An example of such legacy projects leading to more than 70 scientific publications is the APEX Telescope Large Area Survey of the Galaxy, ATLASGAL[4], conducted with the LABOCA facility instrument[5].

APEX also participates as a VLBI station of the Event Horizon Telescope (EHT) aiming at high resolution imaging of the close environment of supermassive black holes in our Galaxy and in nearby galaxies. For this purpose, the PI heterodyne receiver at 230 GHz from the MPIfR, permanently installed in one of the Nasmyth cabins is regularly used. (see e.g. Wagner et al. 2015, A&A 581, A32).

2.1 Requirements for Daytime Observations

To allow for observations at THz frequencies, the surface of M2 and all M1 segments are highly reflective at FIR wavelengths, but also to sunlight. Considering the collecting area of the 12-m M1 aperture, this implies the severe risk of substantial damage to several telescope components if the antenna points close to the Sun position, which therefore must be avoided always. There are various failure scenarios, which can force the system into this situation. The most prominent case happens when the antenna points near zenith and it cannot be moved away in elevation due to a drive or control systems failure, while the sun approaches its transit just before solar midday. Also, other known cases exist where the antenna drive system control loop failed and moved the antenna into the drive axes hard limits, which requires manual operation at the local control panel of the drive system to recover an operational state. Various other failure scenarios end up in similar dangerous situations, that could lead to illuminating the antenna by direct Sun light.

To avoid the scenarios described above, a 30° circle was defined called the “sun avoidance circle”, centered at the sun position on sky, within which the antenna is not allowed to point during observations. An audio alarm is alerting the telescope operator in the control room, if this happens e.g. while the telescope is tracking a source on sky moving into this circle. When the antenna is commanded to point to a target on sky and the direct trajectory between the target position and the antenna’s current position crosses the sun avoidance circle, the trajectory is modified accordingly to circumnavigate the forbidden zone. Zenith position failure modes as mentioned above, require that during the period of the day in which the zenith position itself is located within the circle, there are no science operations carried out and the antenna stays secured in its park position. This period of the day is called “sun avoidance time”. Figure 2 indicates the period within a given year, starting in which sun avoidance time occurs.

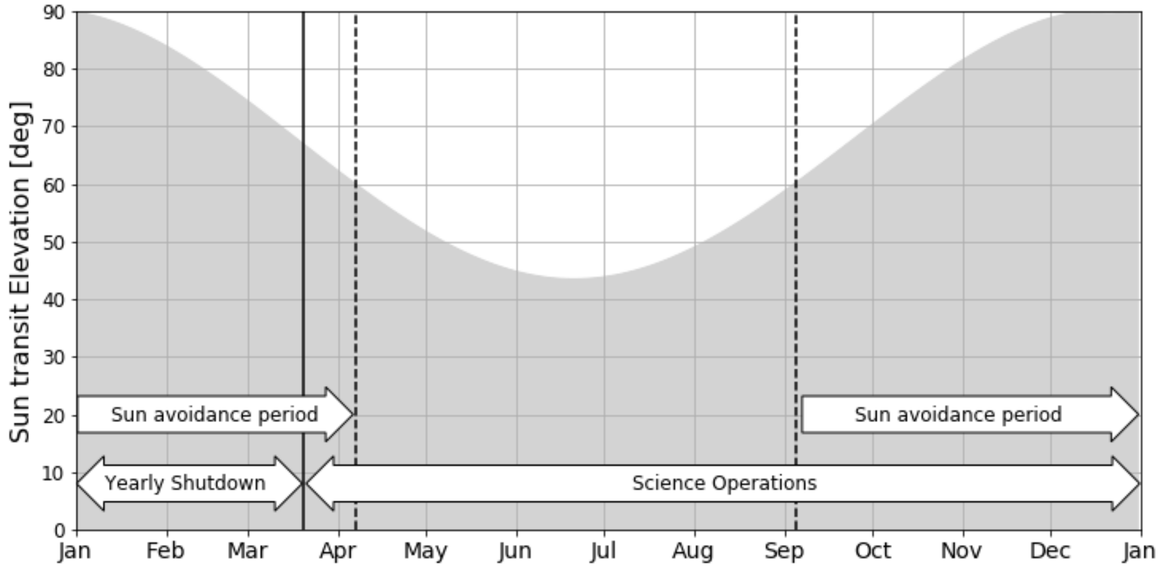

Figure 2: The plot shows the elevation angle of the sun in transit over a year and indicates the science operations period between Marth 19th and December 19th as well as the yearly shutdown period. During the period from around April 8th to September 4th, science operations are daily interrupted during the so-called sun avoidance time (see text for details).

Many of the known failure modes require recovery procedures through the low-level control of the telescope drive system from its local control panel. For this reason, since the beginning of the project, daytime observations have been carried out from a control room at the high site, close to the antenna. This allowed for immediate interventions by the telescope operator in case of sunlight critical failure modes. This necessity has posed for years strong constraints in the antenna operation scheme. Day observing shifts with a telescope operator and a visiting astronomer had to be conducted in harsh environmental conditions, while night shifts were mostly done from the base station at San Pedro. This implied at least two daily commuting trips between both sites for the two daytime observing shifts, which accumulated 1.8 FTE per year in only commuting for the total of 80000 km driving route. The consideration of these resources, the safety aspects of the high-altitude work and of the driving conditions formed the requirement to develop an alternative remote operation concept for daytime science operations, called SciOps-R[emote], which we implemented in 2017 and describe in Section 4.

3. ENGINEERING PROJECTS FOR 24H REMOTE OPERATION

During the last 3 years, starting in 2015, various technical improvements have been designed and implemented to enable 24h remote observations from the base station in San Pedro, minimizing the risks described in section 2.1. The implementation of a Sun Avoidance System (SAS), as a failsafe concept to eliminate this risk, was the major milestone for the 24h remote operation project. The layout of this concept is described in section 3.1.

Moreover, the envisaged concept also defined new requirements to engineering and maintenance operations. Given there was a guaranteed science operation team presence at the telescope location from before sunrise to sunset (up to 13.5h a day, depending on the epoch of the year), troubleshooting of technical issues was also supported by the telescope operator.

This support comprised quick checks on the status of subsystems or manual operations e.g. simple resets of systems. Taking this into account, the remote operation concept had to consider the requirement that there is no compromise on the operation efficiency. An increase of technical downtime as a consequence of remote operation was not acceptable. Consequently, all telescope systems have been reviewed in order to identify monitoring and remote-control requirements. Moreover, Failure Mechanism and Criticality Analysis (FMECA) have been conducted on system level, to identify the requirements on redundancies as well as on remote control strategies to react to failure cases. Failure mechanisms which are known to trigger an avalanche of secondary failures, if not immediately stopped and resolved, had been in the particular focus. Exemplary, we describe how we implemented solutions for two systems, in sections 3.2 for instrument cooling and in section 3.3 for the microwave link.

3.1 SAS – The Telescope Sun Avoidance System (SAS)

The core functionality of the SAS is an automatism implemented in the telescope drive system PLC, that automatically aborts the current Apex Control System[6] (APECS) command execution and immediately moves the antenna into its safe park position. The implementation of this automatism required the replacement of the original PLC to a more modern model. In general, the correct execution of APECS commanded moving patterns during science operations is a complex control task. When commanded to a point on sky the drive system accelerates the 125t moveable mass of the antenna to a velocity of up to 6 arcdegrees/s in azimuth and 3 arcdegrees/s in elevation and decelerates accordingly to point to the commanded position on sky with an accuracy of better than 1 arcsecond, followed by accurate tracking of the target trajectory on sky with better than 0.5 arcseconds. Upon that, the PLC algorithms also consider the correct execution of the conventional movement patterns typical for radio telescope observation modes as on-off target switching, on the fly mapping or even spiral mapping modes. The replacement of the PLC, involving the translation of the software code into a different language, as well as for the implementation of the SAS software block, were contracted to the telescope vendor, VERTEX Antennentechnik, in Duisburg, Germany.

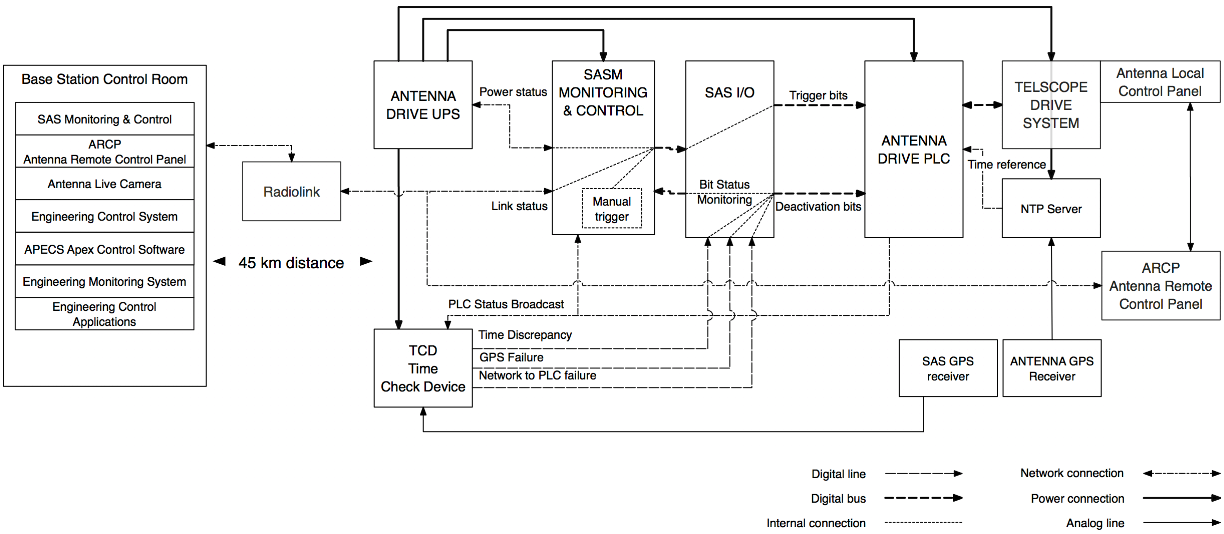

Figure 3: The schematic layout of the SAS and its interconnections with the telescope drive system and with the remote-control room in San Pedro is sketched in this figure. Please see the explanation given in the text for guidance through this diagram.

The diagram in Figure 3 describes the functionality of the SAS system. One of the main tasks of the SAS software block in the PLC is to continuously calculate the current distance between the telescope position on sky and the current sky position of the sun. If the distance between those positions reaches a minimum threshold, the SAS interlock in the software block is internally triggered, causing the PLC to abort the current command execution and to initiate the immediate movement to the antenna park position. The current antenna position is measured by additional encoders and compared to the read out of the high precision encoders of the drive system. This provides a verification in the position sensing that rules out a failure mechanism induced by a false encoder readout. For the calculation of the current sun position on sky, the PLC is synchronized to time provided by an NTP server, locked to a GPS signal. In order to verify that the PLC actually is using the correct time, it is broadcasting this time in an internal network that combines all SAS subunits. One of these subunits is the Time Checker Device (TCD). The TCD is synchronized to its internal NTP server that is locked to a second GPS receiver, and compares both, the TCD time with the broadcasted PLC time. In case the calculated deviation reaches a defined threshold, it has to be assumed that the PLC is not able to calculate the correct sun position. In this case, the TCD sets a digital IO port at the PLC input, that causes the PLC SAS software block to de-activate the sun avoidance interlock for the distance criterion described here. The same functionality applies for an error state of the TCD GPS receiver or a network problem in the broadcast network (see digital IO lines in Figure 3). The de-activation of the sun avoidance interlock for the sun distance criterion is a failure mode. When entering this mode, the antenna has to be moved to its safe park position remotely controlled by the telescope operator, following a defined procedure. For this and other cases, there is a manual trigger option implemented in the SAS control (see middle block in Figure 3) to initiate the safe movement of the antenna into park position.

The SAS interlock is not only automatically activated by the internal PLC SAS software block. Further conditions for a safe remote operation of the antenna at daylight have been identified and correspondent processes have been implemented in the SAS system. Obviously, the network connection between the base station control room and the high site is required to be functional at all times. Therefore, the network status is monitored by the SAS Monitoring & Control System which is connected via digital bus to the PLC IO ports, through which the SAS interlock can be triggered as well. This is executed automatically, if the network to the base station is faulty or as well if the status of the ANTENNA DRIVE UPS requires this. This 57KW UPS has been installed to provide the electrical power to move the antenna in case of a power cut at the high site. In addition, all relevant SAS system units are connected to this UPS. A third digital IO line that triggers the SAS interlock, is the manual activation bit (located in SASM Control). This can be directly activated by the telescope operator in any case of uncertainty of the state of the system at the telescope.

There are failure modes in the telescope drive system that disable the antenna control system from the drive system. These failure modes require manual intervention at the Antenna LCP (Local Control Panel, see right upper corner in Figure 3). The variety of necessary interventions ranges from a simple reset of the servo system to manual control of a single the drive axis to move the antenna, which is the lowest control level possible. Acceleration and velocity, however, do not follow the profile algorithms applied at higher command levels, which makes this operation very critical. In order to remotely control the LCP, we have developed a full emulation software of all control buttons and indicators of the LCP on a computer (ARCP – Antenna Remote Control Panel) that controls the LCP via its analog lines. This kind of remote operation on the lowest control level is very critical. Live cameras showing the antenna movement in the control room, support the operator in such situations. There is a training that certifies the operator for this kind of operation. Additionally, the engineer on duty (EoD) has to be present in the control room to verify and support all actions (buddy principle).

It is not in the scope of this publication, to provide a complete description of the SAS and its functionalities, as well as of the possible failure modes that the system is designed to handle. The intention here is to describe the approach we followed to implement remote operation on such a complex system. This approach certainly would not have been selected when the remote operations requirements were specified for the original design of the drive system. As such, we provide here a remarkable demonstration on how complex a retrofit on operation critical systems can be.

The SAS system has been installed and commissioned during February and March of 2017. Since April 2017, APEX is operating in the SciOps-R mode successfully, 24 hours a day. Various different kind of failure modes, incidents in the antenna drive system, network problems, and sun distance criterion incidents, in which the SAS interlock was triggered, have been successfully safeguarded by the wide range of functionalities the system provides, finally proving the failsafe design of the system.

3.2 Failsafe Instrument Cooling

Along the evolution of the telescope instrumentation, APEX as of today has the capability to operate 9 instruments at a time, 3 in each instrument cabin. Closed cycle Helium compressors cool down and keep the instrument detectors at operation temperatures between a few tenth of a Kelvin (continuum cameras) up to 4.3 Kelvin (heterodyne instruments). All compressors are cooled by a secondary cooling circuit, transferring the heat out of the telescope to chiller heat exchangers. The accumulated heat power with a maximum of 10 He-cycle compressors, peaks at 80kW.

Various failure mechanisms that cause the secondary cooling cycle to either stop or operate in low efficiency exist. Such a failure, however, immediately triggers an avalanche of secondary failure mechanisms. If the secondary cooling circuit fails, the cooling medium warms up, causing the He-cycle compressor to shut-down. The effect for the instruments is similar to a cut in the primary electrical power. All instruments start to warm up and science operations are disrupted. The seriousness of this failure mechanism chain is explained by very long recovery times hurting the efficiency of operations. Typically, 20 to 60 min after a breakdown of the instrument cooling the instrument temperatures reach thresholds where cryo-pumped frozen O_2 and N_2 gasify, causing an excursive breakdown of the vacuum, which enhances the slope of the temperature gradient, by adding the effective convection process to the heat transport. requiring the instrument cryostat to be pumped again before re-starting any cool-down process. The recovery from such a failure mechanism avalanche effect takes 12 hours or more, not counting the fact finding and repair of the originating cause of the failure.

In order to minimize this failure scenario, we have installed a parallel glycol circuit as indicated in the schematic shown in Figure 4. In the upper left and right side, the main and redundant glycol chillers are indicated. Each of them consists of a pair of chillers in series, a compressor chiller and a Dry cooler, providing as such a level of redundancy. Both, the main and the redundant side, feed the glycol circuit for the 10 He-compressors, one at a time. The transfer from the main to the redundant system can be initiated remotely from the APEX base station, automatically carrying out the transfer sequence, switching on the redundant system and electric controlled valve in the glycol circuit, selecting the active chiller system. Each compressor can be switched on or off remotely as well through a remote interface. This also can be used, to lower the heat load, in case of partial failure in the glycol system, to gain time for on-site trouble shooting missions, requiring 75 minutes before any engineering team can arrive at the site. The chiller system parameters are monitored and can be graphically displayed in the control room, for diagnostic purposes. Additionally, the state of each He compressor, its individual electrical current value, glycol return temperature and flow rate are sensed and also can be displayed in the control room as well. The He-compressors configured in parallel circuit, 5 in parallel per 2 main parallel circuits. Each circuit is equipped with a pressure sensor, also fed into the monitoring system.

In an electrical power cut scenario, this configuration provides the cooling capacity of 1800l Glycol/H_2O mix. An 80kVA UPS with a capacity of 50KWh is installed to supply the main or redundant Dry cooler, the He-compressors and the auxiliary equipment to monitor and control the system. Through the remote control from the base station control room, a configuration can be selected to adapt the system lifetime to the expected recovery of the electrical primary power, e.g. only 2 instruments are kept cold, Dry cooler cycle time adjustment to make use of the existing cooling capacity of the glycol reservoir, etc. Since 2018 all facility instruments are equipped with individual turbo molecular vacuum pumps, directly flanged to the instrument cryostat, so that pumping can be initiated remotely in case an uncooled instrument faces a vacuum breakdown.

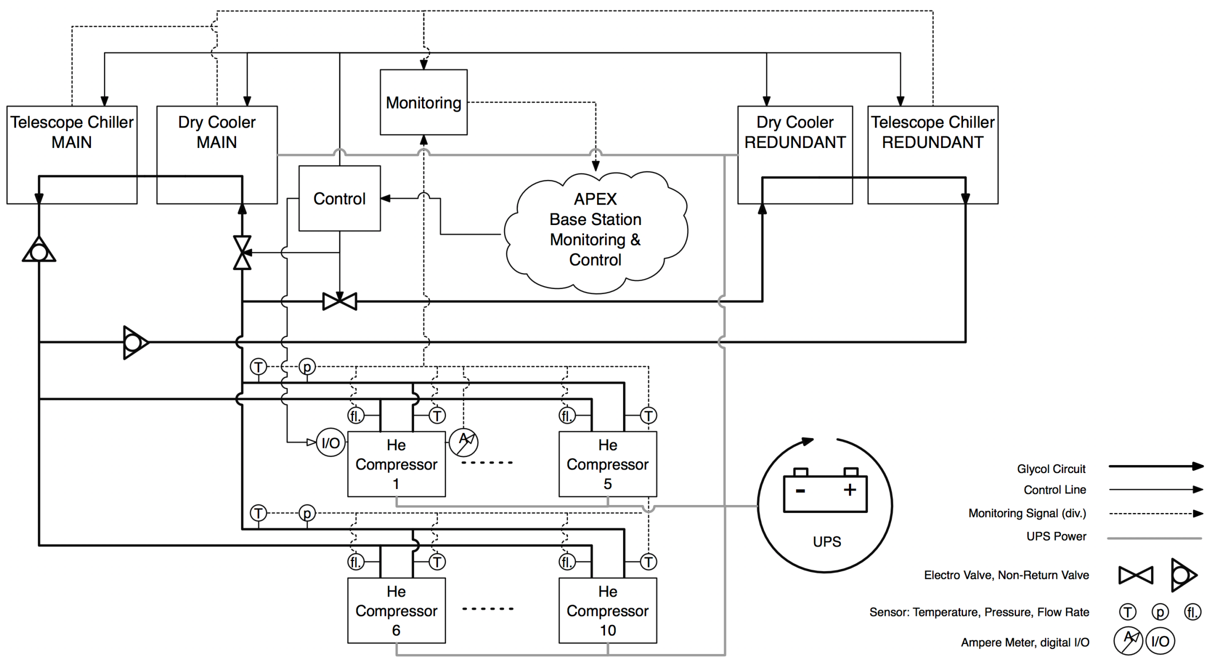

Figure 4: Schematics of the redundant secondary instrument cooling system circuits as well as their monitoring and control.

3.3 Operating a Microwave Radio Link at 5158 m.a.s.l

It is obvious that a reliable network connection between the operation center and the remote site installations is the most essential for continuous remote operation. Therefore, this was the first project carried out to prepare the observatory for remote operation. To guarantee the functionality of the network connection a fully redundant microwave link (MWL) is the core of the system concept. An additional backup system, similar to the concept of the electrical power generation at the high site with 2 redundant generators and 1 backup generator, a low bandwidth radio link (LBL) ensures basic functionality to safely shutdown the telescope and to monitor basic parameters for diagnosis, in case of a failure in the redundancy (e.g. caused by a lethal lightning strike). The Cerro Chico summit, where the radio link is located (see Figure 1), is exposed to extreme harsh environmental conditions. Very high wind velocities up to 120 km/h with correspondent wind chill temperatures below -50°C can occur, defining additional requirements to the layout of the system. Upon that, thunderstorms at the Chajnantor plateau often produce lighting strikes at this location, at which the installation of effective lightning rods are not trivial. Unfortunately, our installations there are hit by lightning strikes with a rate of approximately 1.5/y, and in 2018 a severe strike damaged equipment in both branches of the redundant MWL. This indicates that our concept does not provide full reliability and requires further improvement in the lightning protection.

Figure 5 sketches the layout for the redundant MWL comprising of 2 parallel links, both operating at a time. Each link has a bandwidth allowing 300 Mbps, sufficient for science operations. In case one link fails, the trunk router manages the transfer of connections through the remaining link.

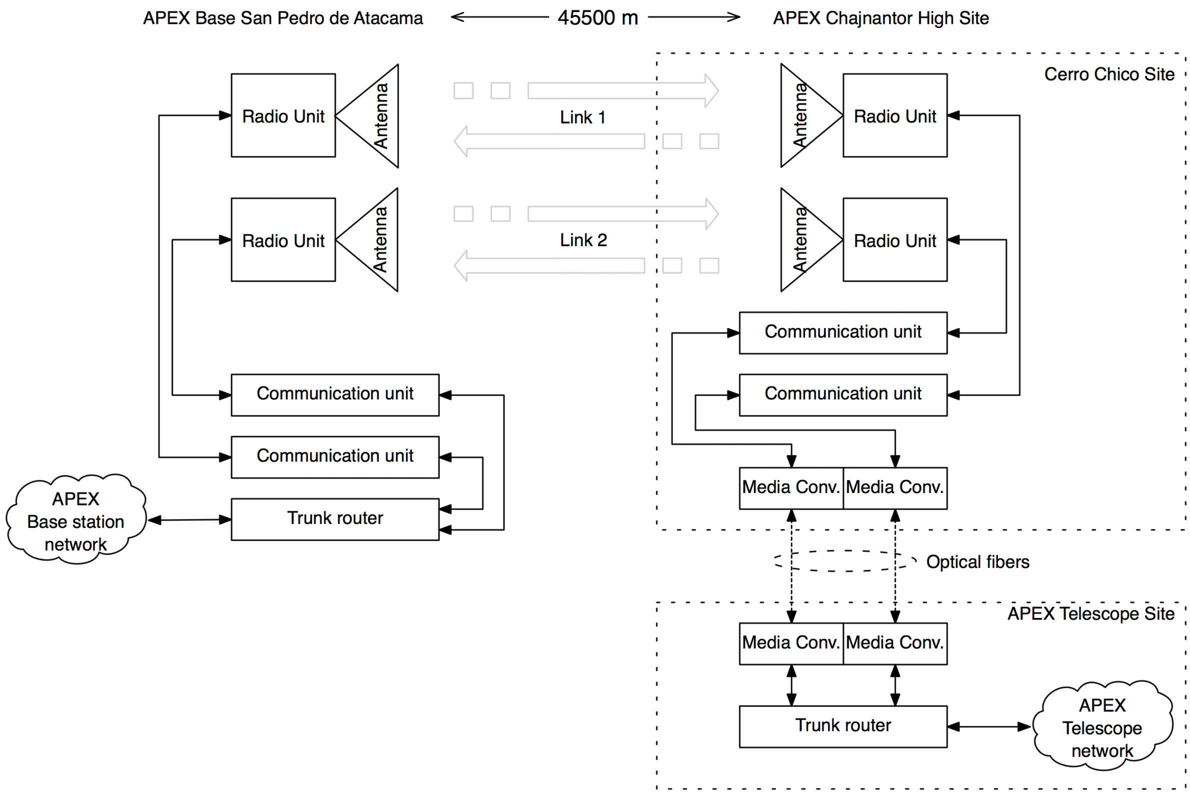

Figure 5: Schematic layout of the redundant MWL connecting the networks between the telescope high site and the Apex base in San Pedro de Atacama.

The concept of a redundant system (MWL) with an additional backup (LWL) is implemented in various critical systems at the high site. The electrical power plant at the high site, based on diesel power generators works with the identical concept. An automatic transfer station controls the transfer of the electrical grid to the redundant generator in case the prime system indicates a problem. A third generator, as a backup, is started, if the transfer to the redundant fails.

Figure 6: At the summit of Cerro Chico, 1.5km away from the telescope, the radio link antennas are directed to the APEX basecamp with a direct 45.5km line of sight. The photo shows the MWL antennas on the right side in the background. In the foreground the panels of the solar plant are visible, mounted on the lee side of the container. Therein, a small thermally isolated compartment is built that hosts the electronic equipment of the link and the solar plant. The equipment's heat dissipation keeps the temperature of the battery bench above -10°C at outside wind-chill temperatures of -40°C. Not visible on the photo is the 25dB gain Yagi antenna of the backup LBL, mounted on the same pole as the MWL antennas.

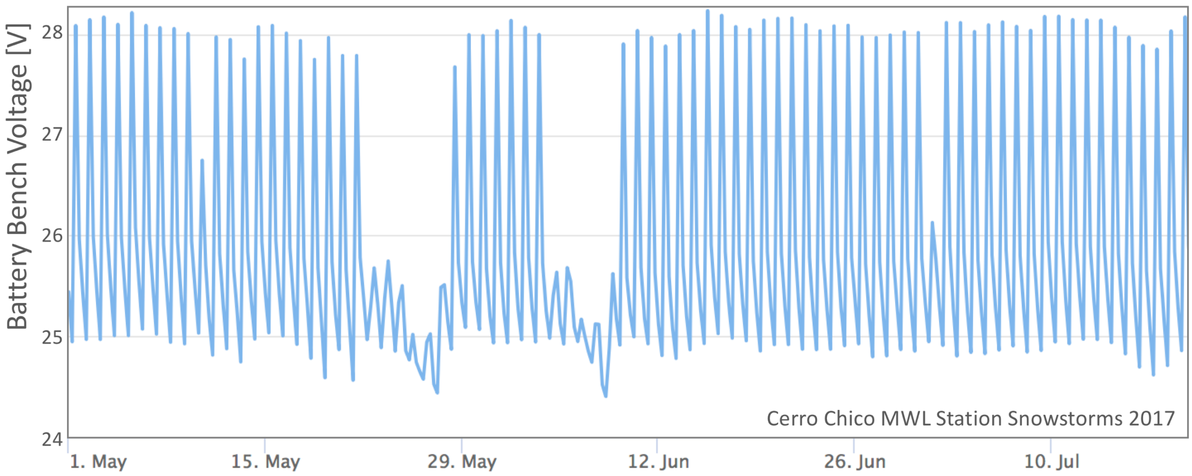

Figure 7: Monitoring data of charge/discharge cycles of the Cerro Chico seen in the 24V batterie bench voltage from May to July 2017. Two long snow storms occurred on 22nd of May (5 days) and 4th of July (4 days) inducing no or little solar energy into the bench. The critical threshold is at 22V, where the link switches off. In these period, both, main and redundant link, were running at a time, defining maximum power of 200W.

Due to the distance of 1.5km from the MWL link site at Cerro Chico to the APEX telescope, electrical power is not provided through the electrical grid from the telescope. Attempts to do that failed in the past for various reasons. After several lightning strikes synchronously at both sites, these attempts have been stopped and interconnecting cables were removed. Cerro Chico is now fully self-sustainable by means of a solar power plant (see Figure 6). The battery capacity of the 24V link installations has been laid out to provide electrical power for 120h without charging, to safely survive long snow storm periods, typically occurring in winter time during June to August. The solar power charging cycles and all states of the equipment is fed into the monitoring and control system. In case the battery capacity reaches a low threshold during the night, due to low charge during the day, the monitoring system creates a warning. In crisis conditions, during long snow periods, one link can be remotely switched off, reducing the energy consumption by a factor of 2, which doubles the remaining time to a total discharge threshold and failure of the link. An example for the performance of the solar energy plant is shown in Figure 7, showing the battery bench voltage vs. time from May to July 2017 with 24h cycles of sunlight charging during 24h of constant energy consumption of the link equipment. On May 22nd, a snow storm period of 6 days with less solar energy charging during these days, shows the negative balance between daytime charging and 24h consumption, resulting in a voltage drop of 0.5V to 24.5V. As during these weather conditions, the antenna operations are shutdown, the consumption can be remotely reduced by a factor of 2, in order to gain time before the battery discharge passes the critical threshold of 22V. The monitoring system creates correspondent warnings at 24V.

3.4 Holography Experiments at 5450 m.a.s.l per mouse-click from San Pedro

The 12m main reflector of the APEX cassegrain telescope has to keep its surface RMS below 15 microns to allow for submillimeter observations. The 264 aluminum segments are adjustable[7], with 5 adjuster screws each, to minimize the deviation of the reflector from the parabolic shape. A table providing the adjustments for each of the 1320 screw adjusters is derived from a holographic picture of the reflector representing the deviation of each segment with a spatial resolution of 6.5 cm. The hologram is measured with a classical antenna test range setup at 92.4 GHz. The antenna under test is rotated around its phase center receiving a signal from a transmitter. Phase and amplitude are recorded to derive a classical antenna diagram. In order to cancel phase drifts of the transmitter, the receiver and atmospheric instabilities along the line of sight between the two, a reference receiver, phase locked with the receiver in the antenna under test, is used to eliminate these. This reference receiver is mounted at the backside of the secondary reflector, whereas the main receiver is mounted in the cassegrain focus of the telescope. Hence, phase differences in the antenna diagrams represent optical pathlength differences, from which the M1 surface deviation can be derived by means of Fourier Transformation[8]. The existing setup for this re-occurring measurements has been re-designed and was replaced by a new system. Both heterodyne receivers have now integrated local oscillators, which are directly fed by a common low frequency base oscillator. This replaces manual tuning of waveguide back-shorts of the gunn diode oscillators[9] and as well the tuning of the PLL, allowing for reliable remote control of both receivers. The compactness of the new design also allows the mounting of the main Rx on a high precision translation stage (see left hand photo of Figure 8), to precisely and remotely move the instrument into the secondary focus for operations, when selected by the APECS (Apex Control Software) as it is executed for any other instrument. This implies that the system can stay continuously installed in the cassegrain cabin, which is an enormous advantage to the replaced unit. For each of the earlier holography operations, the 30kg heavy receiver had to be installed and de-installed after the holography experiment, creating an overhead of 2+ days for this work, blocking any other operation of the telescope.

A similar step forward has been made with the installation of the re-designed new transmitter. Instead of a gunn diode oscillator at 94GHz with manual back-short tuners, a customized high-power AMC-I built by Virginia Diodes[10] has been integrated, which is by a low frequency base oscillator with integrated PLL. With this new layout for the Tx, no manual adjustments or tunings is required anymore. The supply electronics and monitor lines are connected to an ADAM® module which connects via a low bandwidth radio link to the monitoring and control software of the Tx in the APEX base station in San Pedro. Figure 8 shows the Tx subunits on the right-hand photo. The upper aluminum box contains the RF part, whereas DC voltage supplies, network interface and radio link Tx/Rx are located in the lower compartment, shown open on this picture, which was taken during the installation mission[11] in 2016. The transmitter is located at 5450 m.a.s.l, slightly below the peak of Cerro Chajnantor. at a direct line of sight distance of 1800m to the APEX antenna. Reaching the transmitter location, requires a 950m climbing tour with an average slope of 35% and maximum slopes up to 65% on bed load and rocky ground. The track is indicated in the overview of Figure 1. Whereas the old transmitter required such missions 2-3 times a year, the new Tx is now operated since 2016 without maintenance.

The enormous enhancement of efficiency in the operations, introduced with the new holography system, offers now a wider range of studies of the surface quality of the primary and secondary mirror. Gaps in the science operations, e.g. occurring at high precipitable water vapor above 4mm, can now be used to immediately schedule "holography observations". During scheduled technical time, holography experiments can now be easily scheduled into the technical observations plan. Consequently, we expect to obtain better insight into surface deformation processes [e.g. day/night cycles] as well as we aim to achieve higher surface quality (< 10 microns RMS).

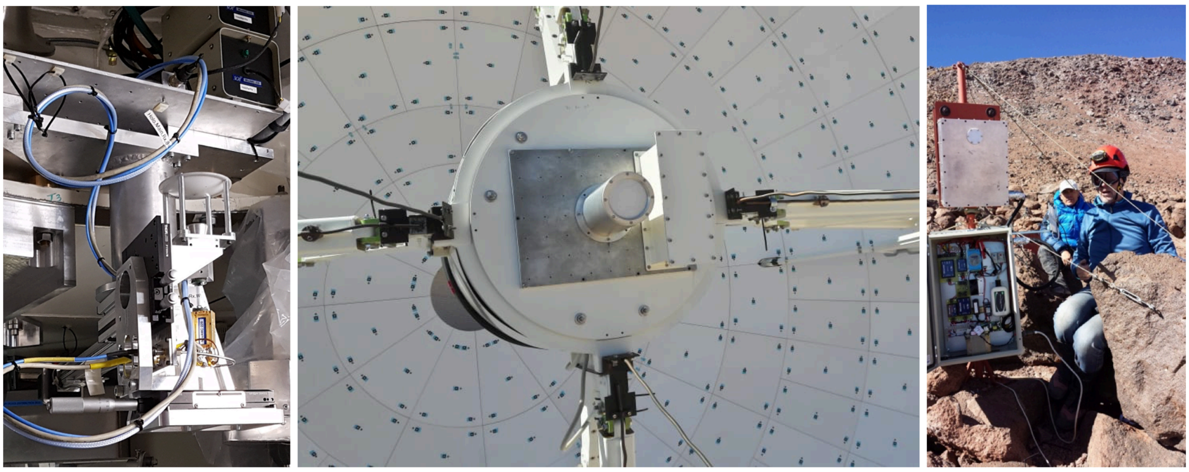

Figure 8: The photos show the 3 units of the new holography system. On the left side, the main Rx is shown mounted in the cassegrain cabin. The receiver can be remotely moved into the secondary focus. The middle photo shows the reference Rx, mounted backwards from M2 and directly pointing to the Tx. The right photo shows the transmitter at the installation mission in 2016. For a more detailed description, please see text.

3.5 Engineering Data Monitoring and Control for Remote Operation

In order to prepare the observatory for remote operation, a monitoring system has been developed that gathers all monitoring points into databases for further use. As of today, in total 1991 monitoring points of the various systems are stored with a default period of 1s. Discussions on whether it is necessary to gather all this data are valid. However, often monitoring points, that never were considered to be useful to store, suddenly become very valuable, e.g. for studies of failure mechanism analysis (FMEA) out of monitoring data. The author made this particular experience in the published HIFI Anomaly[12] of the HERSCHEL mission day 81.

A network monitoring tool with graphical interface in the base station control room is used to continuously monitor 151 IP addresses, relevant for the remote operation. The tool reports the status and warns on flaky or suspended network connections. In case of a problem, the tool provides the necessary overview on all affected networks and IPs as part of the failure mechanism analysis taking place in the control room.

268 engineering monitoring points have been identified to be critical for flawless remote operation. These are currently selected for live display by means of the monitoring graphical interface that is continuously used in the base station control room to provide all status information to the observing team in the control room, in particular warnings or alarms on faults. Figure 9 shows the main window of this graphical interface. On the left side the monitoring points are grouped into areas. A warning or alarm occurring in an area is indicated by a color change of the button, and dependent on the criticality by an audio signal in the control room. On the right side, the list of monitoring values of a selected area is displayed and can be selected for a graphical display vs. time. Additional groups of values or multigraphs can be selected that open in additional windows. With these features, the EoD can quickly arrange the display of all information needed. This is not only used for live FMEA, but also for general support of engineering tasks. During maintenance operations at the high side (in parallel to the ongoing observations), the EoD coordinates all activities with the responsible high site engineer and safeguards any configuration change from the control room. If, for example, engineering maintenance requires the transfer of the high site electrical grid, from the active diesel electrical power generator to its redundant generator for a scheduled maintenance, the EoD will display all relevant monitoring points for this transfer and supervises this operation, finalized by a confirmation that no telescope system was affected by the transfer. Any operation configuration change is logged manually into a database that stores the whole operation configuration history of the telescope. This enables correct monitoring data analyses of historical data. A dedicated display in the control room shows the current operation configuration of all subsystems, as this is necessary for remote operation.

Each monitoring point has 2 adjustable ranges that define the warning and the alarm threshold. It is the task of the EoD (Engineer on Duty) to adjust these ranges appropriately, in particular when configuration changes require this. This task also is considered to avoid unnecessary warnings and alarms to the observing team.

Figure 9: Main window of the Monitoring System graphical interface in the base station control room in San Pedro

4. 24/7 REMOTE SCIENCE OPERATIONS: SCIOPS-R

SciOps Remote (SciOps-R) constitutes the second major upgrade in the operations scheme at APEX, 7 years after the implementation of the 24-h operations mode in 2010. The implementation required a substantial upgrade of technical functionalities to guarantee the safety of operations and its efficiency, as exemplary described in the previous sections. Here we briefly describe, how science operations is implemented in the remote operations concept of SciOps-R.

4.1 The Base Station Remote Control Room

The base station control room, 68km away from the telescope, is the center of operations. Here, remote observations are conducted merged with remote engineering. The control room (see Figure 10) is composed by three main operation stations in its central part, in front of a larger central display unit, a matrix of 10 displays providing information visible for everybody working at those stations, respectively the engineer on duty (EoD), the telescope operator (TIO) and the visiting or staff astronomer. The central display unit contains all engineering graphical interfaces for remote control and monitoring on the left-hand side 6 display units, whereas the remaining 4 displays provide monitoring information important for the execution and planning of observations. The observing stations contain all necessary tools correspondent to the task distribution in the observing team triple:

The Engineer on duty (EoD) supervises the engineering activities from the left side terminal (see Figure 10) . He/she oversees the status of all systems and initiates engineering interventions if necessary. During nighttime, the EoD can be called by the TIO, in case of anomalies reported by the monitoring system, requiring his expertise to assess or to intervene. In case of SAS incidents (see section 3.1), the EoD supervises critical operations of the antenna drive systems. During high site engineering activities, he/she supervises the activities and receives reports by the assigned high site engineer (HsE). This ensures that the detailed configuration of the system is available at any time in the control center, which serves safety aspects as well as the configuration control of the various hardware states of all subsystems, visible on the central display. Any deviation in the original planning determined in the daily morning coordination meeting requires the approval by the EoD, as well as any change requested in the hardware configuration of the system. He coordinates all activities in parallel to the telescope operation conducted by the TIO. The EoD oversees the status of all systems and initiates engineering interventions if necessary. During nighttime, the he/she can be called by the TIO, in case of anomalies reported by the monitoring system, requiring his/her expertise to assess or to intervene. In case of SAS incidents (see section 3.1), the EoD supervises critical operations of the antenna drive systems. During high site engineering activities, he/she supervises the activities and receives reports by the assigned high site engineer (HsE). This ensures that no activity interferes with the observations conducted in parallel.

The telescope operator (TIO) conducts all observations and takes over the EoD tasks in his/her absence, particularly during nighttime. The observation task comprises the beside the control of APECS, furthermore quick data analysis and calibrations. He oversees the atmospheric conditions and takes this into account for the further planning of the observations.

The visiting or staff astronomer in the observing team, oversees the projects to observe during the observing shift and coordinates directly with the TIO. He/she assesses the information provided by the TIO and arranges the short-term planning accordingly. He/she is supported by the AoD in the background to discuss specific questions coming up during the observations.

Communication tools for the observing team to the outside of the control center are provided with the radio communication station and telephones, as well as with a skype terminal to communicate with a high site team or to participate in the daily coordination meeting. There is also space reserved for visitors who can work in the control room to support the visiting astronomer (see terminals on the right side in Figure 10), in particular during PI instrument campaigns. On top of these terminals, a display shows the assignments of responsibilities during the observing day as well as the operation planning details and their updates during the day.

Figure 10: Sequitor control room for Sciops-R operations. On the left area, the observing team has available the observing tools and monitoring information to conduct science operations. The engineer on duty has assigned a working station where he can monitor the systems and coordinate actions with the observing team and the high site engineer. The right area is used by visiting observers who can work while following up the course of the observations.

The control room configuration is kept strictly, and the operation follows strict procedures. These determine rule on how activities at the high site are carried out, how telescope operations are carried out and how to react in cases of anomalies of the system. The system integrity is a condition to approve remote operations in the daylight period. A strict protocol is followed in the handover from night to morning shift to verify this integrity. In case of an unsolved issue with the SAS or the drive system in general, remote operations is not approved and the observing team has to conduct the observations from the high site control room, which still is maintained for these cases.

5. OPERATIONS KEY PERFORMANCE INDICATORS

The experimental nature of APEX, with many PI instrument installation, testing and troubleshoot missions, hasn't a strict priority on maximizing the collection of scientific data, as it is also a declared to bring forefront and new technological detector developments to the telescope. The scientific value of this is difficult to express in a KPI, as it is seen as an investment in the future. Each of the APEX partners can decide independently in his observing period on the fraction of time dedicated to technical PI instrument interventions or test campaigns that involve significant telescope time not used for science. In this context, the "operations efficiency" was not well defined. From 2007 onwards though, the metrics "Hours on Sky" was used as a performance indicator for the observatory. The calculation of this number is retrieved from the observing log of APECS which allows to calculate the actual time of each observing scan time stamps, counting from the beginning of the scan to its successful finalization. This number steadily grew per yearly accounting, and in the monthly accounting it revealed "weak months", caused by bad weather conditions or technical issues and other reasons. Figure 11 shows in the upper graph the "Hours on Sky" metric from 2013 to September 2017, and the correspondent cumulative yearly metric is shown in the lower left graph of Figure 11. The interpretation of the yearly metrics of 10 years of steady operations clearly show it evolution. The time between 2007 and 2009 show the ramp up phase. In 2010, operations went from 16h per day to 24h science operations per day, "improving" the yearly statistics by almost 600h compared to 2009. In the following years, until 2014, the yearly "Hours on Sky" metric stagnated on a level of approximately 3850h. In 2013, a valid discussion arose on whether the maximum was arrived or whether this still can be improved. Maintenance strategies have been reviewed and improved. Successively, more engineering monitoring points have been introduced and analyzed to understand failure mechanisms, with first attempts to predict issues and plan corrective maintenance ahead of incidents creating technical down time. In 2014 and 2015 we achieved approximately 4450h, a step of 600h compared to the stagnation period over the previous 4 years, and of similar size as achieved with change from 16h to 24h science operations per day. Another initiative started in 2014 with the introduction of an accounting system to log downtime sorted into different categories (see Figure 11 upper graph for the various categories). This approach was initiated after the review of the "Idle Time" of the telescope. This time can also be calculated from the APECS control system log. The idle time represents the accumulation of time, in which the telescope was not in park, but also neither not in scan mode. Ideally, this idle time should represent the overhead between two scans, created by various activities, e.g. observing project change, target change, etc. and accumulating to not more than 5% of the observing time. With the introduction of the downtime logging, the ideal time should break down into its actual fractions. In the upper graph of Figure 11, the implementation of this can be followed. 2014 shows the first fractions of logged downtime for the various categories. We also introduced a category "PI Instrument Overhead" accounting all PI instrument interventions as discussed above, to define a clear differentiation between downtime that is created by APEX operations (and subject to review), and non-operational time outside the influence of APEX operations, like the weather downtime and time for PI instrument interventions. The 2014 data clearly shows that the idle time decreased a little. Better training of the telescope operator in the downtime accounting and the development of a software tool for the accounting system started to show positive effects from March 2015 onwards. Important for the further discussion is the understanding of the "Hours on Sky" for 2017 in the lower left graph. Since on 25th of September onwards, science operations were terminated for a 6-month period for a Telescope overhaul involving the replacement of M1 and M2, the "Hours on Sky" (3285h) cannot be compared one to one to the previous years. Therefore, we extrapolated this number, based on the "Hours on Sky" of 2016 counted until 30th of September (3245h). On this basis, the extrapolation yields 4807h considered for the long-term statistics.

In general, we conclude from the long-term statistics we present with the "Hours on Sky" (lower left graph in Figure 11), that the improvements in the operations plan have led to an increased efficiency of operations. This, on the other hand, also implies that the original plan did require these improvements, or vice versa, it implies that the operation efficiency suffered in the past from a non-optimal operations plan. This leads to the valid discussion, whether operation plans for observatories are considered at the right level of detail in the design of observatories. Requirements that specify the efficiency of an observatory should be verified not only in technical design reviews of a telescope and its subsystems. Furthermore, an operation concept, worked out to a detailed level in a correspondent operation plan, needs to be made subject to review in order to verify its compliance with high level requirements of observatory efficiency, at the same time when the hardware design is reviewed.

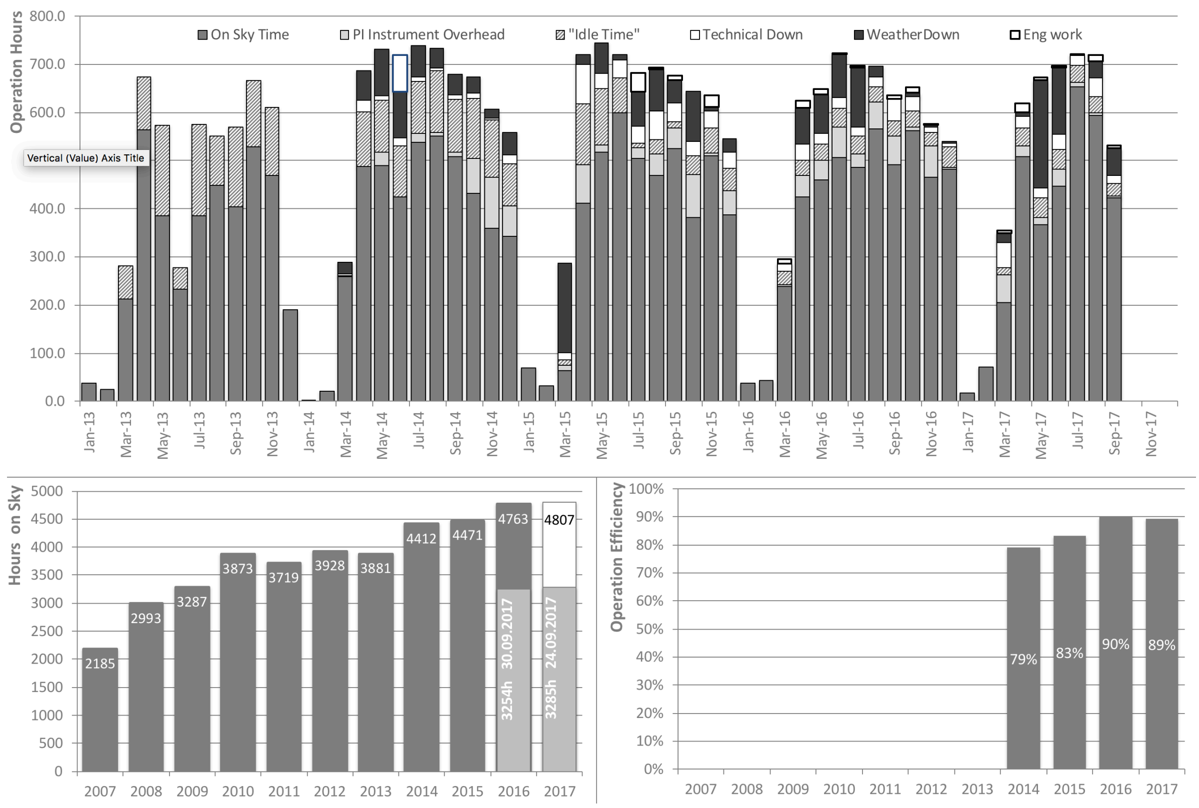

Figure 11: Summary of metrics development of KPIs for operations at APEX, starting in 2014. See text for a more detailed explanation.

Summarizing the above discussion, the downtime statistics can be assumed to be reasonably correct for 2016 – 2017, accounting the correct sum of technical downtime and engineering work as a KPI. This yields around 5% in 2016 and 2017 and is at the same level as the idle time for these years. A series of 4 years can be considered though if we add the idle time as a third fraction of the metrics for "Operation Efficiency". This metric is shown in the lower right graph of Figure 11 and shows qualitatively a very similar pattern as the "Hours on Sky" for the same years (left side graph).

In summary, with the introduction of the various downtime categories in 2014, we believe that after the full implementation of the correct logging in 2015, that we have reliable data to calculate operation efficiency KPIs for 2016 onwards into the future. As this efficiency qualitatively appears to be similar to the long term "Hours on Sky" we prove that the observatory is improving its operations efficiency continuously since 2013 after a stagnation of several years.

6. SUMMARY DISCUSSION AND OUTLOOK

We have presented several examples for the retrofit designs of our upgrade programme, transferring the science operations of APEX to a remote 24h per day operation scheme, SciOps-R. This remarkable technical effort was necessary to fulfill two main requirements: The technical risk of accidental sun illumination of the primary mirror must be controllable in all failure modes, without manual intervention at the remote site at 5107 m.a.s.l., 68km away from the base station control center. Secondly, the introduction of remote operation must not introduce additional technical downtime due to the absence of personnel at the remote site. After the implementation of the upgrade, we have verified in operations year 2017, that both requirements were met. Moreover, the introduced tools and operation protocols will contribute to an even increase of efficiency and data quality. The upgrades of each subsystem also considered in their design, that they keep their functionality for a certain period, even when primary systems fail. Instrument cooling now is supported up to 90 min, after a primary power cut would occur, valuable time for engineers to fix a problem before avalanches of secondary failures are triggered. Reliable remote control and monitoring also guarantees control of the system, when the site must be evacuated, or if it is not accessible due to the environmental conditions. In those situations, the APEX systems can now be controlled through such a period. Accordingly, the recovery of science operations, e.g. after a long snow storm, is not delayed because subsystems failed during a longer period of personnel absence. This is in particular important for the Chajnantor site, as here typically the best atmospheric conditions (precipitable water vapor < 0.3 mm) occur right after such snow storms.

Remote monitoring and control of telescopes become more and more important. Operations of telescopes, planned to be built in even more harsh environments (e.g. CCAT-p on Chajnantor summit at 5600 m.a.s.l) will have to consider operations thoroughly and include these aspects into the hardware design. Retrofit designs and their implementation can be complex and expensive, compared to their consideration in the original design. The combination of cost and complexity can reach a level that excludes the implementation and can define the limit of the operation efficiency of an observatory. That applies to all ground-based observatories. The concepts of distributed sites operation, where several telescopes are operated from a central location, aim to make use of synergies. These potential synergies suffer if the operations concept of the single site is not designed for remote operation. It is therefore recommendable to consider operation plans of telescopes in the earlier project phases to the appropriate level, than this is usually the case. The ESO Paranal Observatory (PAO) considers the integration of two new observatory sites into an operations concept that operates the E-ELT and the CTA, centralized at and merged with Paranal operations. Strategies and their aspects, as they have been discussed here, will be worth to study when developing an operations concept for PAO with its distributed sites.

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