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# Flight Operations and Lessons Learned of the Rosetta Alice Ultraviolet Spectrograph

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**This paper explores the uniqueness of ESA Rosetta mission operations from the Alice ultraviolet spectrograph instrument point of view, documents lessons learned, and suggests operations ideas for future missions. The Alice instrument mounted on the Rosetta orbiter is an imaging spectrograph optimized for cometary far-ultraviolet spectroscopy with the scientific objectives of measuring properties of the escaping gas and dust, as well as studying the surface properties, including searching for exposed ices. Described within this paper are the operations processes during the comet encounter period (2014–2016), the many interfaces to contend with, the constraints that impacted Alice, and how the Alice science goals of measuring the cometary gas characteristics and their evolution were achieved. Details are provided that are relevant to the use and interpretation of Alice data and published results. All these flight experiences and lessons learned will be useful for future cometary missions that include ultraviolet spectrographs in particular, as well as multi-instrument international payloads in general.**



## I. Introduction

AT FIRST sight of the comet 67P/Churyumov-Gerasimenko, it was obvious that the Rosetta mission would be different from any that came before. Although this was expected to some extent, as reflected in the mission design, the need for an even more complex concept of operations was realized when the highly irregular comet body was finally resolved 10.5 years after launch.

The shape of comet 67P is composed of two unequal (2–4 km) lobes with a deep neck area connecting the two. This added complexities in the gravity field, the nonuniformity of material and light coming off the surface, and the geolocation mapping. The combination of these factors along with the anticipated difficulties of orbiting a low-gravity dynamic body that creates its own ever-changing environment result in truly unique mission challenges that require equally unique operations solutions.

As a member of the Jupiter-family comets, 67P's highly elliptical orbit takes it just past Jupiter's orbit (5.684 au) and almost as close to the Sun as Earth (1.246 au) every 6.45 years. The result is a periodic transformation between a dormant, dark, frozen nucleus near aphelion and a spectacularly dynamic display of sublimating gas and entrained dust near perihelion. This strong variation in activity drove many Rosetta mission attributes and constraints, adding to the already complex system that included the Rosetta orbiter with 11 instrument packages and the Philae lander with its own set of 10 instruments.

Because the comet activity evolved as it circled the Sun, the Rosetta and Alice operations processes evolved through the mission to provide a system that could meet the ever-changing needs. Tools were redesigned, interfaces were changed, and processes were updated to optimize science return.

After launch, the circuitous path of Rosetta included several orbits in the inner solar system, including three gravitational assists from Earth and one from Mars; the last Earth flyby sent Rosetta to the outer solar system on a rendezvous path with 67P. During this long cruise phase, Rosetta's instruments were able to make observations of Earth; comet LINEAR; comet Tempel 1 during the Deep Impact Mission event; Mars; asteroid Steins; and asteroid Lutetia, which allowed testing out the flight systems and ground processes. Rosetta entered an unprecedented 2.5-year hibernation period when the spacecraft was at the outermost part of its orbit, which took it out to the orbit of Jupiter, where it only had enough solar power to have a few vital heaters and electronic units on [1]. There was no contact with the spacecraft: not even beacons during that hibernation period. An onboard timer was set to tell Rosetta to wake up on 20 January 2014, when there would be enough power to turn some additional systems on and contact Earth. Everyone was on the edges of their seats on hibernation exit day, to say the least; amazingly, all systems turned on and proceeded with the comet encounter period 10.5 years into the mission.

Shortly after exiting that hibernation period, Rosetta began studying comet 67P in a manner never before attempted at a comet. Where previous missions had studied comets from flybys of several hundreds of kilometers away and traveling at relative velocities of tens of kilometers per second or performing a brief surface impact, Rosetta's two-year encounter period was often spent at tens of kilometers from the comet nucleus with relative velocities of meters per second. A slow, controlled surface impact concluded the historic mission, adding to the high surface resolution measurements that the Philae lander acquired at the beginning of the encounter. Table 1 details some of the important Rosetta mission and Alice instrument

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**Table 1 Major mission and Alice events (N = North, S = South)**

| Date | Event |
|---|---|
| 2004, March 2 | Launch |
| 2004, April–May | Observations of comet LINEAR |
| 2005, March 4 | Earth flyby no. 1 |
| 2005, July 4 | Observations of Deep Impact |
| 2007, February 25 | Mars flyby |
| 2007, November 13 | Earth flyby no. 2 |
| 2008, July 19 | Alice upset/reset event no. 1[a] |
| 2008, September 5 | Asteroid Steins flyby |
| 2009, September 29 | Alice upset/reset event no. 2[a] |
| 2009, November 13 | Earth flyby no. 3 |
| 2010, July 10 | Asteroid Lutetia flyby |
| 2011, June 8 | Spacecraft hibernation entry (4.5 au)[b] |
| 2012, October 3 | Aphelion (5.3 au) |
| 2014, January 20 | Spacecraft hibernation exit (4.5 au)[b] |
| 2014, March 18 | Alice first power on after hibernation[a] |
| 2014, June 6 | Alice begins continuous powered operations[a] |
| 2014, August 6 | Orbit insertion at comet 67P, start of encounter period |
| 2014, November 12 | Lander delivery (3.0 au)[b] |
| 2014, November 15 | Lander hibernation begins[b] |
| 2015, March 28 | Spacecraft star tracker safe mode: instruments off[b] |
| 2015, April 15 | Alice returns to nominal operations after safe mode[a] |
| 2015, May 10 | Equinox (N vernal, S spring) |
| 2015, June 13–Jul 9 | Intermittent lander contacts[b] |
| 2015, August 13 | Perihelion (1.2 au) |
| 2015, September 4 | Solstice (N winter, S summer) |
| 2016, March 20 | Equinox (N spring, S vernal) |
| 2016, May 28 | Spacecraft star tracker safe mode: instruments off[b] |
| 2016, June 1 | Alice returns to nominal operations after safe mode[a] |
| 2016, September 30 | End of mission (3.8 au) |

[a]Alice event.
[b]Spacecraft or Lander event.



events based on the Rosetta mission operations reports of the Alice logbook.

In Sec. II, we describe the Alice ultraviolet spectrograph design and science objectives. In Sec. III, we describe the operations of Alice and the various instrumental and mission constraints that affect the operations. Section IV covers the different types of Alice observations, supporting observations by other instruments, and the special issues regarding making observations while orbiting an active comet. In Sec. V, we describe the broader context and design of the Rosetta mission operations. Section VI provides some lessons learned and additional information.

## II. Alice Ultraviolet Spectrograph

### A. Alice Design

Alice is a lightweight and low-power imaging spectrograph optimized for cometary far-ultraviolet (FUV) spectroscopy [2]. It was the first of a family of similar instruments currently including Alice on New Horizons, the Lyman Alpha Mapping Project (LAMP) ultraviolet spectrograph (UVS) on the Lunar Reconnaissance Orbiter, the UVS on Juno, and the UVS instruments on the upcoming Jupiter Icy Moons Explorer and Europa Clipper missions. The scientific objectives of Alice included measuring the properties of escaping cometary gas and dust, as well as studying the comet surface properties, including searching for exposed ices. Science objective details can be found in Ref. [2]. Rosetta Alice was the first UV spectrograph to study a comet at close range.

Alice was designed to obtain spatially resolved spectra in the 700–2050 Å band with a spectral resolution between 8 and 12 Å for extended sources that fill the field of view. The field of view is a slit design that is described as a “dog bone”: it is 5.53 deg long in the spatial dimension, the central 2 deg of which (called the “narrow center”) is 0.05 deg wide in the spectral dimension, and the 2 deg “wide bottom” and 1.5 deg “wide top” portions of the slit are 0.1 deg wide in the spectral dimension [2]. A pinhole feature at the top of the slit was never detected in flight. Further Alice instrument design details can be found in Ref. [2].

### B. Alice Science Modes

The Alice instrument has three modes of taking data: histogram, pixel list, and count rate. They were described in more detail in Refs. [2,3].

In histogram mode, the instrument continuously collects detected events by pixel location throughout the exposure, much like how a charge coupled device counts and accumulates detected photons. During the course of a histogram observation, each detected event is saved into memory, where the memory locations map one to one to pixels on the detector. In this way, an integrated spatial-spectral image is accumulated over the commanded exposure time. The resulting images are $1024 \times 32$ pixels (16 bit), with the long $X$ axis (perpendicular to the slit) corresponding to the wavelength; and the short $Y$ axis (parallel to the slit) is the spatial dimension. The physical area of the detector does not extend the full range of the $1024 \times 32$ region mapped to memory, and so some parts of the resulting image never contain any detector data. Also, the slit does not extend the full height of the detector, and so some parts of the detector do not get illuminated through the Alice slit field of view. These active but unilluminated detector regions and the image parts not containing detector data are used by the flight software and data pipeline to place auxiliary engineering data. The histogram values (counts) saturate at 65,535 counts. This was the most commonly used mode during the mission, and the data volume was deterministic because the size of a histogram exposure is a fixed value, which is independent of the observed flux.

In pixel list mode, the instrument serially records the $x$-$y$ location of each photon and inserts time tags (“hacks”) in this list at regular user-definable intervals to provide the timing information for the photons. The result is a list of events that contains positional information with interspersed hacks providing timing information. Because the Alice data memory is 64 KB, it fills up when this pixel list has 32,767 (16-bit) entries; at which point, Alice stops the exposure to dump the data to the spacecraft before being able to start another exposure. This means that, for long exposures, there can be “gaps” in the Alice pixel list data if the source is bright enough to fill up the memory during an exposure. It also means that the amount of data collected will be a function of the observed flux through the Alice field of view, making it difficult to predict the data volume during planning. For these reasons, the pixel list mode is not used as often as the histogram mode. The pixel list mode is employed primarily during the bimonthly cross-slit scan calibration due to the need for time resolution to detect when the star crosses the edges of the slit.

In the count rate mode (also called the “photometer” mode), the spatial and spectral information for each photon is ignored. The instrument reports only the number of photons detected in each user-defined time interval up to a limit of 65,535 counts in an interval. This mode is not widely used, but it could be useful for observing targets with very high count rates or stellar occultations, or when there are significant data volume constraints. The number of intervals is independent of the brightness of the target, and it is deterministic during planning as simply the number of time intervals within the total exposure time (up to a total of 32,767 such intervals before Alice data memory is filled), and the exposure stops to dump data to the spacecraft.

## III. Alice Operations and Constraints

### A. Contamination

The material coming off the comet posed a serious mission risk because the fine dust and gas could coat instrument optics and solar panels, which could lead to severe science degradation, could decrease spacecraft power production, and could prevent spacecraft attitude and location knowledge determination. Furthermore, during periods of high comet activity, there were unpredictable, strong outflow events that quickly propelled concentrated jets of material outward. Large pieces of material were seen orbiting the comet and, at times, navigation camera (NavCam) and Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) images showed that Rosetta was flying through a blizzard of dust particles, as shown in Fig. 1 [4,5].

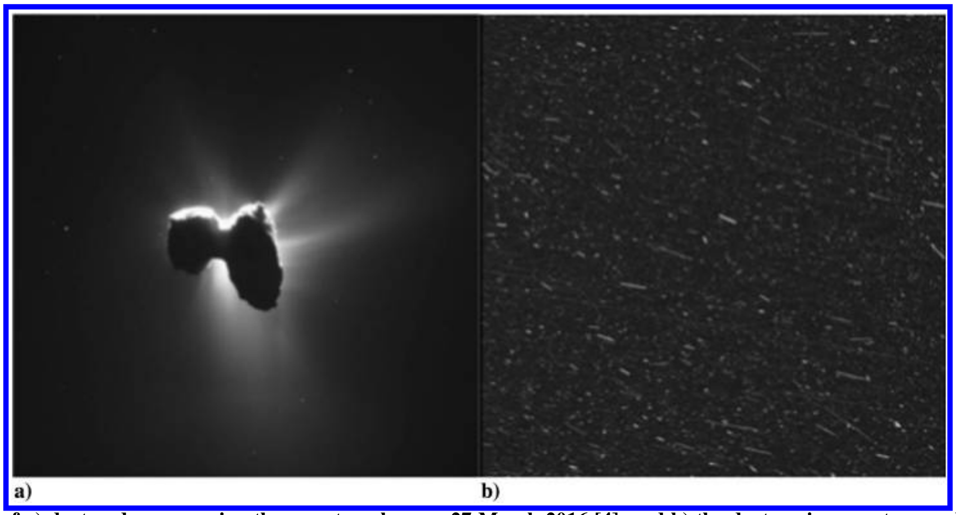


**Fig. 1 Photographs of a) dust and gas escaping the comet nucleus on 27 March 2016 [4], and b) the dust environment around Rosetta captured by Rosetta's OSIRIS camera on 6 July 2015 [5].**



It was difficult to strike the right balance between what was perceived to be a safe distance from the material coming off the comet and being close to the nucleus to obtain high-resolution measurements and significant counts for the dust and gas instruments. For Alice, the local gas pressure and dust count measurements never reached sustained levels that would cause great concern of contamination, and the levels were always below limits that would have triggered an Alice safing event that closed the aperture door and turned off the detector high voltage. Regular calibration observations with the Alice instrument through the escort phase tracked sensitivity degradation, which was minimal, due to contamination and other sources.

However, one system affected by the dirty environment was the spacecraft star trackers that occasionally would get confused by the bright dust particles and lose attitude knowledge [6,7]. That resulted in two spacecraft safe events that halted all activities to regain attitude knowledge (Table 1), and there were several other close calls. This failure of the star tracker acquisitions resulted in increasing inaccuracy of inertial attitude knowledge on board the spacecraft and, if it lasted long enough, it could lead to subsequent loss of communications to Earth and risk of impact on the nucleus. To safeguard against such mission fatal risks, the project erred on the side of caution and usually kept a robust margin on the distance to the comet based on activity. This typically helped Alice science because the spectrograph's long slit (5.53 deg) at these larger distances allowed Alice to have some spectral elements on the nucleus and others looking off-limb at the escaping gases in tandem (as a "ride-along") with observations designed by other instrument teams that preferred surface pointing (see the Fig. 2 example [8]). Another factor that possibly helped preserve the Alice throughput is that the instrument operated in continuous decontamination mode for most of the encounter after verifying it did not impact instrument calibration. This meant that the mirror and grating heaters were constantly enabled to keep those optical elements warm, so they would not be cold traps, by driving off any deposited contamination. However, given that there were very few problems or failures for components on the Rosetta orbiter through the encounter phase demonstrated that encountering high concentrations of material and large destructive chunks of material was rare, even though the environment was much dirtier than typical when orbiting less active bodies such as planets, moons, and asteroids.

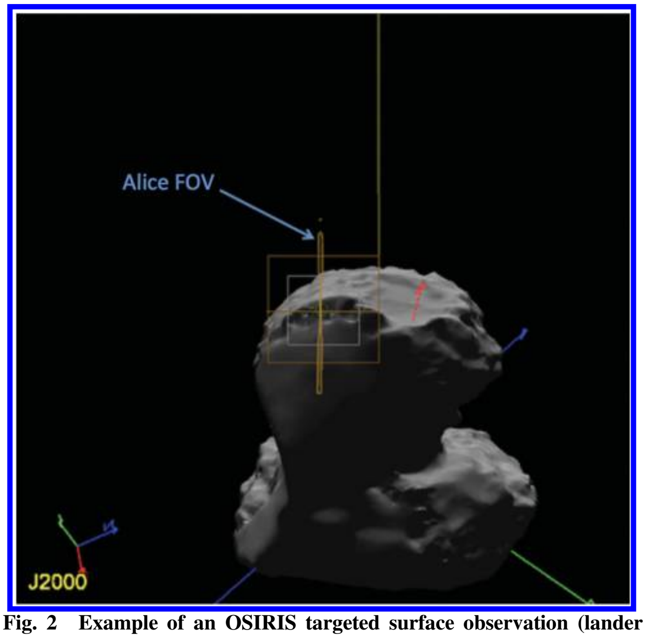


**Fig. 2 Example of an OSIRIS targeted surface observation (lander search) that could be used by Alice as a ride-along to simultaneously view the nucleus and offcomet gasses [8] The Alice FOV is shown in yellow.**

### B. Gain Sag

Adding some additional constraints to the Alice operations, the instrument has an unscrubbed microchannel plate (MCP) detector. The scrubbing process exposes the detector to UV light, reducing the pixel charge: a conditioning technique that "burns in" the pixels, eventually stabilizing the detector response. However, a scrubbed detector imposes significant constraints in preflight ground handling, including a requirement of being kept in constant vacuum, which is not an option in this case because the Alice bandpass in the extreme ultraviolet requires an open-faced detector. The consequence of flying an unscrubbed detector is that its response continually decreases through the mission from exposure to UV light, which is a typical characteristic of MCPs called "gain sag." The gain sag is also spatially dependent as a function of the total fluence on a given area of the detector, leading to nonuniform sensitivity degradation across the detector. For example, the varying brightness of the comet surface, the observation of bright UV stars on specific detector rows, or the constant exposure to Lyman-alpha emission from the interplanetary medium will cause some parts of the detector to degrade differently from other parts. Figure 3 shows three sample time periods of the progression of the total number of counts accumulated on the detector over the course of the escort phase, simply by summing up all of the images obtained during that time period. Because gain sag is proportional to the number counts, Fig. 3 serves as a proxy map across the detector of the progression of the gain sag. The degradation is tracked using stellar calibration observations discussed in Sec. IV, is accounted for in the data calibration, and is periodically

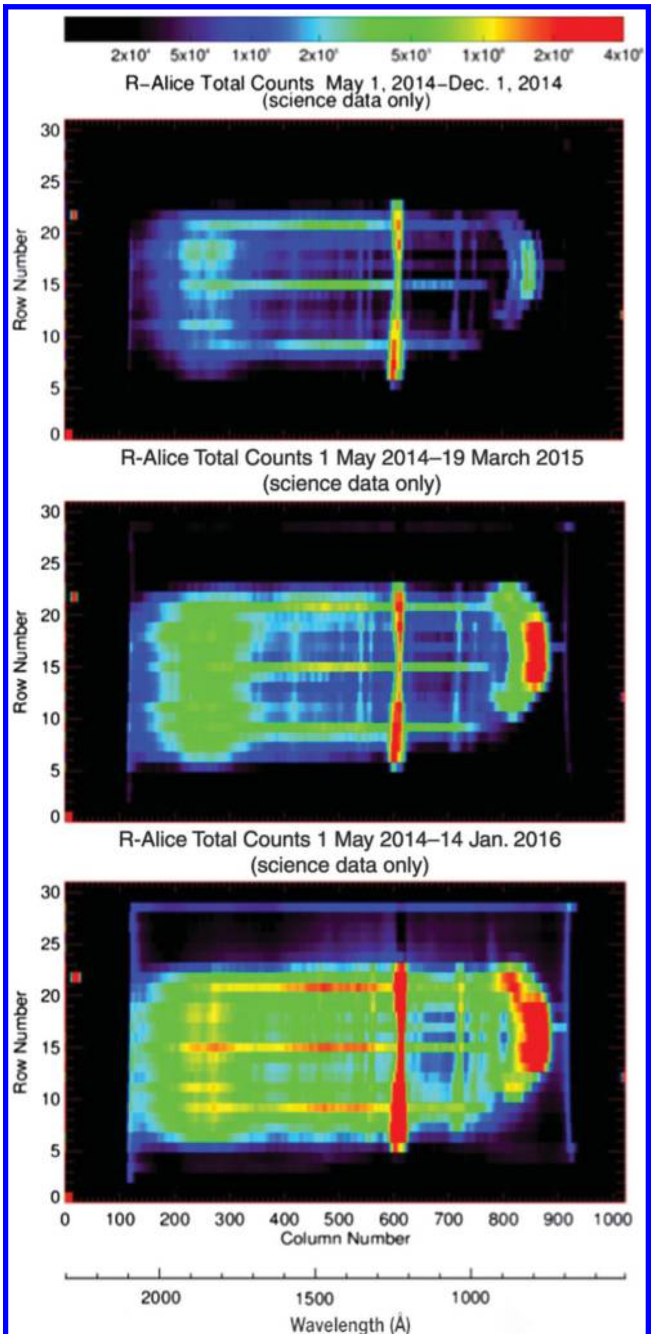


**Fig. 3 Progression of detector science counts through encounter. Gain sag increases proportionately to the total fluence of counts at each point, and so this figure also effectively shows a map of the progression of gain sag across the detector. The concentration of counts near column 600 (1215 Å) is the Ly-$\alpha$ line, and the region around column ~850 (~850 Å) corresponds to the chameleon artifact region. The high concentration of counts in rows 9, 15, and 21 is due to stellar calibrations. In this figure, the detector column number increases to the right, and the wavelength increases to the left.**

compensated for by changing detector settings such as the high-voltage level (a detector sensitivity adjustment) and discriminator level (a signal cutoff adjustment). Characterization of the detector performance is conducted periodically using moderately bright UV stars as calibration sources.

The anticipated long-term gain sag drove strategic planning for the detector usage to ensure that the detector would maintain adequate sensitivity throughout the mission in critical bands and detector regions to satisfy the science goals. This initially drove analysis-intense observation constraints of conducting only high-priority comet measurements and actively avoiding exposure to relatively bright UV stars.

### C. Bad Dogs and Chameleons

Some stars were so bright in the UV that they could cause excessive count rates on the Alice detector. These UV-bright stars were nicknamed "bad dogs." The Alice team would receive the predicted spacecraft attitude and location information and use it to determine when bad dog stars would cross the Alice field of view (FOV) plus a margin to account for pointing uncertainty. The team would then adjust instrument commanding to suspend the Alice observations and close the aperture door around the forecasted bad dog encounters. Making the process even more complex was that the planned spacecraft attitude could change late in the product development process due to other instrument teams adjusting their prime observations or by the mission flight dynamics team adjusting the comet orbit plans. This would require agile monitoring and response from the Alice team to quickly (sometimes as short as within a couple days) identify and make corresponding Alice observation changes.

As the mission progressed, it was determined that the detector gain sag rate was lower than initially projected, which allowed the gain sag avoidance techniques to become progressively less conservative. By the end of the mission, Alice was observing almost continuously, and bright UV stars were no longer manually avoided. Instead of avoidance planning, a detector count rate monitor with a configurable threshold was relied upon to react when any too-bright stars came in the FOV, autonomously safing the instrument by temporarily pausing the observing and closing the aperture door. The momentary exposure to the bright source did not significantly contribute to the overall detector gain sag and was a welcome tradeoff between some loss of exposure time in exchange for significantly reducing the labor-intensive star avoidance planning.

The other primary contributor to bright safety events came from a sporadic issue referred to as the "chameleon," which was thought to be due to charged particles entering the instrument, getting through the detector electron grid, and causing strange high-count measurement artifacts (see Fig. 3) [9]. Because the chameleon had strong temporal variations, usually, the bright safety action of temporarily closing the aperture door and waiting the safety timeout period (typically 10 min) was sufficient to deal with the occasional high-count-rate chameleons.

### D. Alice Observing Styles

Throughout the mission, Alice would observe during both Alice-planned (termed "prime") observations as well as observations planned by other instrument teams (termed "riding along"). Even though many observations designed by other teams were not optimized for Alice science goals, some science return was always possible when observing the comet and its surroundings. However, potential science return always had to be balanced with available spacecraft resources, development effort, and the expected gain sag impact. Alice observing consisted of two main styles. The first was continuous observing, in which histograms were taken one after another (with short ~40 s overhead for image readout between exposures) for many hours at a time, and was not correlated to a specific scene or pointing changes. This was simple to implement, but it could produce data that were difficult to interpret, such as when histograms bridged changes in spacecraft attitude, staring, and scanning motions; or major scene changes. The other type was to manually time histograms to correlate their start/stop times with specific viewing conditions. Although this technique could often return better science, this style had a high cost in terms of development effort and commanding complexity. This was especially true when timing histograms during ride-alongs because other instrument teams would often change their pointing plans during the development period, which usually required corresponding adjustments to Alice observations. At the beginning of the mission, the Alice team focused on its prime science, refraining from observing during pointing planned by most of the other teams.

However, as the mission progressed, the use of ride-alongs increased when the data volume and other resources were available to a point where Alice was observing almost continuously. This was especially true after it was evident that the gain sag progression rate was less than expected, and software tools were created to automate observation development based on planned pointing characteristics.

### E. Aperture Door Usage and Power Cycling

Alice instrument operations are unlike a lot of other space instruments in terms of power cycling and mechanical door operations. Due to the risk of power-up failures, the action of power cycling space electronics has long been avoided and, on some missions, only done when forced to because of a failure on one string of a redundant system. By necessity, this operational method was not an option on Rosetta. Power constraints during the first and last couple of months of the mission required instruments and some nonessential spacecraft components to alternate powered activities, leading to many unavoidable component power cycles. Power was not a constraint during the other periods of the escort phase.

During the escort phase (August 2014–September 2016), standard Alice operations were to power cycle the instrument on a weekly basis. An Alice upset/reset event occurred twice during the cruise period getting to the comet (see Table 1 for the dates). The anomaly would power cycle Alice and restart in a default state defined by hard-coded parameters; although it would return to the nominal activity timeline, science data quality collected afterward could be negatively impacted until manual adjustments were commanded to several operational parameters. The root cause of the upset/reset events was not identified, but it was thought that periodically power cycling the instrument could perhaps prevent such a problem from occurring or would return Alice to its nominal state if an upset occurred. With some power cycles already required and four separate copies of flight software in memory to boot from, it was decided that the risk would be lower to perform regular power cycles rather than being on continuously. Additionally, to mitigate the impact of an upset/reset event, activities were split into small independent segments, and several operational parameters were reasserted twice daily.

The Alice aperture door operations were similarly different from most other space mechanical systems. Whereas most mechanical systems (and doors especially) are designed for one time use, the Alice aperture door was designed to be opened and closed many times; it was rated for 10,000 such "flaps," which gave a factor-of-two margin relative to ground tests. Alice relied on a robustly designed aperture door mechanism proven by extensive ground qualification testing and, subsequently, by later versions of the instrument. The LAMP UVS, which is a version of Alice on the Lunar Reconnaissance Orbiter mission, has performed over 100,000 cycles. As a safeguard, Alice also had a failsafe door that could be opened permanently to retain some science ability if the aperture door failed to shut. The motivation for all the door cycles was the instrument's susceptibility to contamination and detector gain sag. To avoid contamination of instrument optics from spacecraft thruster byproducts, the aperture door was closed during (and for 30 min after) every spacecraft propulsive maneuver. To avoid contamination from cometary material, the aperture door was also closed for gaps in observations of more than 15 min through most of the encounter, and even shorter gaps when the comet was especially active. Monthly door performance tests confirmed the mechanism exhibited no measurement trends that would cause concern for continued regular use.

## IV. Alice Observations

### A. Orbiting a Comet

There was a preliminary encounter phase timeline outlining an initial plan of Rosetta's orbits around the comet; but, due to the unique cometary environment, it took some time for the mission teams to get used to operating around a comet and refine the plan. In addition to the standard engineering and environment models needed for interplanetary travel, many unusual factors needed to be accounted for, including orbiting a low-gravity body with an asymmetric gravity field created by the two-lobed comet shape, variable aerodynamic drag due to temporal and spatial variability of cometary activity, navigation with star trackers in an environment with high visual dust confusion, and contamination risks. The orbits varied quite a lot to account for these constraints and to accommodate the requested observational conditions, but the following describes the typical orbit types:

The spacecraft flew low (less than 32 km radius) circular orbits when the comet was less active. This allowed the instruments to obtain high-resolution surface information when the contamination risk was low, as well as to increase source flux for the in situ instruments.

As comet activity increased, the spacecraft orbit was expanded to several hundred kilometers to a maximum radius of about ~600 km around perihelion as a safety precaution, but to accommodate science needs, the mission tried to keep the orbit height as low as safety would allow. Bound orbits were not used when orbiting above ~32 km due to the difficulty of balancing acceleration factors when orbiting a low-gravity body during periods of higher comet activity. Above that height, the spacecraft transitioned to joined segments of hyperbolic arcs that typically resulted in full orbits that were roughly circular in shape. This maintained regular observation conditions for science planning while also providing the security of a safe trajectory that would avoid collision with the comet if control of the spacecraft was lost [1]. The orbits typically were aligned with the terminator to minimize gas drag on the spacecraft and avoid eclipses. The orbit orientation allowed the solar panels to be continuously pointed to the Sun and resulted in the minimum surface area pointing in the comet direction to minimize gas forces on the spacecraft. However, angle offsets were occasionally used to obtain a variety of illumination conditions.

Close comet flybys, as close as 7 km from the surface, were used for high surface resolution measurements.

Distant "excursions" to 1000 km in the tail direction and 1500 km in the Sun direction were used to measure the local magnetic field properties.

Finally, the low gravity comet body allowed for some unusual orbit types that would have required an exorbitant amount of fuel to accomplish if Rosetta orbited a larger body. For instance, sharp turns were used for special activities, including the Philae lander release trajectory, and Rosetta swept back and forth over a single area above the surface in an effort to locate the Philae lander (see Fig. 4 [10]). Because of the low orbital speeds of meters per second, a large change in direction actually could involve a relatively low change in momentum, and thus not a significant use of fuel.

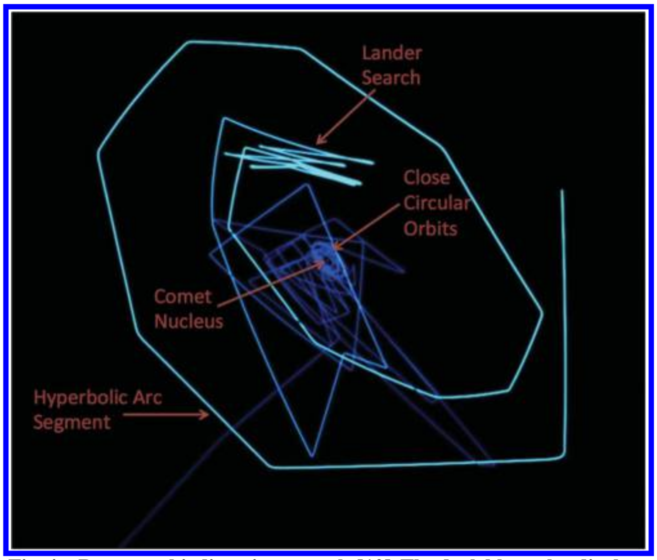


**Fig. 4 Rosetta orbit diversity example [10]. The dark blue color displays the approach beginning 31 July 2014 and early encounter close orbits. The light blue color displays more distant orbits around perihelion through 9 August 2016 and the lander search.**

### B. Pointing Uncertainty

Another unique challenge this mission had to contend with while planning observations was fairly large pointing uncertainties. As is the case for most space missions, the spacecraft flight dynamics team provided the science teams with many orbital parameters to use for planning observations, but unique to this mission was the task of understanding the craft's relative location and attitude with respect to the comet in light of significant nongravitational forces. The spacecraft inertial location and attitude were known very well from the star tracker data and enabled communication with ground stations on Earth and precise pointing at stars for instrument calibrations. However, there were often large uncertainties for the spacecraft pointing relative to a comet reference point, and this had a significant impact on observation planning at several levels. This uncertainty in the prediction of the relative position between Rosetta and comet 67P was due to limited predictability of comet activity (producing gas drag on the spacecraft) and maneuver error (difference between predicted and actual delta-v for upcoming orbit correction maneuvers). For spacecraft pointing relative to the comet reference points such as nadir, limb, and surface locations, this position error translated into a pointing error, even if the inertial spacecraft pointing was accurate.

The pointing uncertainty continually changed, being best just after the current spacecraft location was determined and updated on the spacecraft computer, and then it would grow until the next update as the uncertainties accumulated in the models. The projected comet-relative pointing uncertainty range was typically between 0.1 and 4.0 deg for most of the mission; but, when the spacecraft traveled very close to the comet surface (under 10 km), the uncertainty forecast could grow much larger: up to $\sim$16 deg. In practice, it was found that the difference between the desired and actual pointings could occasionally grow large for short periods of time; however, conservative factors in the models typically resulted in a large overestimate for the pointing uncertainty: typically by at least a factor of two.

Even if observations were planned using pointing uncertainty values of half the forecasted level, the scale of the uncertainties was very difficult for some of the instrument teams to incorporate in their planning. Negotiations for prime observation slots by the remote-observing instrument teams often prioritized slots with low pointing uncertainty values to reduce observation smear and improve chances of targeting specific surface features. However, Alice planning was able to be more accommodating than that for other instrument teams regarding pointing constraints, and so Alice was able to use a lot of prime observations with high pointing uncertainty periods. Making use of these slots was made possible because the Alice FOV was much larger than most of the other instruments (5.53 deg long) and it took relatively long exposures (5–10 min), making observations of specific locations less important than getting good regional coverage. Also, several Alice observation types were off-comet, such as inertial or 360 deg great circles that were not impacted by the comet-relative pointing uncertainty. This made Alice observing much less dependent on the pointing uncertainty values as compared to the other instruments, and Alice was able to put many of the worse pointing uncertainty blocks to good use.

### C. Observation Types

Specific pointing could be developed once the orbit type was defined and the trajectory and subspacecraft parameter details we frozen, such as orbit height, phase angle, latitude, longitude, and pointing uncertainty. After negotiations for observation time were completed, the instrument teams turned their attention to implementing the plans. Each instrument team would tailor the pointing during their prime observations to optimize science return. Teams could verify and iterate the pointing products using mission simulator tools; then, after they were delivered, they were verified and approved by the Rosetta Science Ground Segment (RSGS) group at ESA's European Space Astronomy Centre (ESAC) in Spain and the Rosetta Mission Operations Center (RMOC) group at the European Space Operations Centre (ESOC) in Germany. There were quite a range of observation types implemented by the various instrument teams, but most were variations on these: 1) staring at the surface with the comet rotating underneath the spacecraft, 2) matching the comet's rotation rate to track a surface location, 3) scanning across the surface, 4) staring at one of the comet limbs, and 5) pointing offcomet.

In the following are details of some of the variants of these observation types that Alice used. For reference, the observation names are also used in Alice data nomenclature, which is discussed further at the end of the paper in the Alice Logbook section (Sec. VI.B).

### D. Alice Observation Types: Gas Observations

A primary Alice science objective was to characterize the gasses coming off the comet to better understand the solar system's primordial constituents and environment. This required measuring the different gas types, their relative abundances, and how they varied through the evolution of the comet during its orbit around the Sun. To do this, a variety of observation types were designed to view the gasses against a dark background (either looking offcomet or a shadowed region on the comet), where the reflection of sunlight off of the comet surface would not interfere with the measurements. The styles varied and were refined based on the distance to the comet, gas abundance, and the understanding of the comet environment.

#### 1. *Volatile Abundance Campaign*

A primary style of gas observation used for Alice and other instruments was named the volatile abundance campaign (VAC), which was designed to measure illuminated gasses against the deep space background (a "deep VAC" was a long-exposure version of such pointing). This was a stable staring observation in which the Alice slit would be positioned such that it was approximately half on the comet surface for location context and half off the sunward limb, although the exact position varied due to the pointing error and negotiations with other instrument teams.

#### 2. *Inner Coma Raster*

When the comet was more active, inner coma raster observations would be used, which would stare in several locations, stepping off the comet in a radial line, typically sunward, to track how the gas abundance fell off with respect to the distance from the comet.

#### 3. *Great Circle*

Because Rosetta was near the center of the comet's coma throughout the encounter period, the Alice instrument took full 360 deg "great circle" observations to measure the distribution of the gasses it was immersed in and how they changed throughout the orbit around the Sun. Typically, these great circles were in the terminator plane, although there were some partial great circles (often as ride-alongs on other instrument observations) with different solar elongation angles.

#### 4. *Night Stares*

These observations were designed to look at the illuminated gas between the spacecraft and the comet surface, either on the night side of the comet or over large shadowed regions, which had the useful effect of cutting out the sky background.

#### 5. *Coma Ride-Alongs*

The Alice team also rode along on similar observations planned by other instrument teams such as the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS)-led VACs (termed diurnal VACs) that scanned back and forth along the sunlit comet limb looking for concentrations of activity and the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) instrument snowflakes that were a combination of many offcomet stares.

#### 6. *Stellar Occultations*

Although observing stellar occultations was always part of the observation concept for Alice and other instruments to measure coma gases in absorption, planning those proved to be unfeasible due to the uncertainties in the predicted spacecraft orbit and attitude. However, as UV stars were monitored passing through the Alice FOV, it was realized that it was still valuable to observe stellar appulses even if the line of sight to the star did not get to the absolute lowest layers of the coma just above the nucleus. The Alice team was able to model (within uncertainties) the angular distances from the nucleus of various UV-bright O- and B-type stars to target those that could be observed through the column of gas near the sunward limb of the comet. The large pointing uncertainties and frequent pointing plan changes made planning these observations difficult; but, when such observations were successful, the same star was observed again at a later time far away from the comet as a baseline measurement. These two spectra were compared to measure the level of attenuation in specific bands to characterize gas-type abundance. The technique was initiated late in the mission after perihelion, and so a time history of these measurements throughout the comet's activity cycle could not obtained, but $H_2O$ and $O_2$ abundances were measured from several of the 29 stellar appulse measurement sets [11].

### E. Alice Observation Types: Surface Studies

A secondary Alice science objective was to characterize the comet surface reflectance in the UV and search for surface ices to better understand the comet's composition and morphological processes. For these investigations, two types of observations of the illuminated comet surface were planned.

#### *1. Surface Center*

This style of observation would stare at the surface either directly nadir or with a defined offset from nadir and take continuous histograms as the comet rotated underneath the spacecraft.

#### *2. Surface Scan*

This style would scan very slowly at 0.01 deg/s back and forth from the sunward limb to the anti-sunward limb (spacecraft Y axis, perpendicular to the ALICE slit) or as far as could be scanned within an observation window when close to the comet.

#### *3. Surface Ride-Alongs*

Alice rode along on an assortment of other instrument observations, especially on long stares and the targets of opportunity (TOOs), where specific interesting surface features were stared at and most instruments recorded data to provide a comprehensive study of the area. There was a fair amount of observations optimized for other instruments that Alice did not typically ride along because they would not yield high-quality Alice data. For instance, observations that included high scan rates or short stares of less than 5 min for fast mapping of the surface would smear too much surface area to be of much use for an Alice analysis. Alice typically used 5–10 min histograms for surface observations and 10–20 min histograms for gas observations to balance the measurement signal and spatial resolution.

### F. Alice Observation Types: Calibrations

It was very important for several Rosetta instruments including Alice to characterize their performance with regular calibrations. In addition to the typical instrument optics degradation and alignment changes, each Alice observation contributed to a nonuniform detector gain sag effect that needed to be tracked and accounted for. Moderately bright UV stars were used as stable calibration sources for Alice; however, they typically were far offcomet, and it would take a lot of time to slew to a calibration star's position. Because all the instrument teams preferred to spend as much time as possible observing the comet, calibration observations were coordinated to minimize offcomet pointing time. OSIRIS, VIRTIS, and Alice were able to combine stellar calibration requirements, reducing the total number of instances.

The Alice instrument performed several types of stellar calibrations to track changes in performance:

**Table 2 Nominal Alice high voltage and discriminator settings for the Rosetta mission**

| Date implemented | Settings |
|---|---|
| Initial settings | HV −3.8 kV, discriminator 0.09 V |
| 2006, December 3 | HV −3.7 kV, discriminator 0.34 V |
| 2007, February 23 | HV −3.8 kV, discriminator 0.09 V |
| 2007, September 13 | HV −3.9 kV, discriminator 0.09 V |
| 2014, April 2 | HV −4.0 kV, discriminator 0.09 V |
| 2014, May 12 | HV −4.0 kV, discriminator 0.45 V |
| 2015, June 25 | HV −4.1 kV, discriminator 0.45 V |
| 2016, February 23 | HV −4.2 kV, discriminator 0.45 V |

#### *1. Biweekly Stellar Calibrations*

Biweekly stellar calibrations were used to measure the effective area (instrument sensitivity) by periodically staring at calibration stars and measuring changes in response for three representative locations on the detector.

#### *2. Bimonthly Flat-Field Calibrations*

Bimonthly flat-field calibrations were conducted as a raster scan along the length of the slit of a calibration star to measure relative sensitivity differences across the two-dimensional (2-D) detector. This set of biweekly stellar and bimonthly flat-field measurements allowed for the effective area changes to be applied across the full detector, providing a method of correcting for detector gain sag on a per-pixel basis.

#### *3. Bimonthly Cross-Slit Scan Calibrations*

Bimonthly cross-slit scan calibrations were performed that consisted of raster scans perpendicular to the slit of a calibration star using pixel list measurements to precisely define the instrument field of view. This was important to be able to track and account for the instrument flexure due to changes in thermal environment throughout the mission.

#### *4. Bimonthly High-Voltage/Discriminator Calibrations*

Bimonthly high-voltage/discriminator calibrations were performed by staring at a calibration star and making observations with a set of detector high-voltage (HV) levels and discriminator levels: settings that can be adjusted to change the detector sensitivity. These instrument settings could then be optimized to mitigate gain sag effects. The standard operational high-voltage and discriminator values were changed several times during the course of the mission, as shown in Table 2. These changes were taken into account in the calibrated data, but they might be of interest if working with the raw Alice data.

#### *5. Biweekly Dark Calibrations*

Biweekly dark calibrations were also performed, where histograms were taken with the aperture door closed to measure and account for the detector dark count background.

### G. Navigation and OSIRIS Camera Image Request Context Images

Even to the trained eye, Alice histograms can be difficult to interpret, especially when viewing partially shadowed terrain and the variable concentrations and structures of gas and dust coming off the comet. To aid in the interpretation of histograms, it was very useful to examine NavCam and OSIRIS wide-angle camera (WAC) images taken around the same time to provide context to the scene as shown in Fig. 5 (see Ref. [12], in which the image is horizontally inverted to match the Alice histogram orientation). The timing of the images planned by the spacecraft and OSIRIS teams for their operations and science goals were often not well correlated to important Alice observations. So, in another example of cooperation within the mission to achieve the best science possible, the Alice team was permitted to plan additional NavCam and OSIRIS image requests (NCIRs and OCIRs, respectively) with the constraint that the image data volume was covered by Alice resource allocations. Initially, the

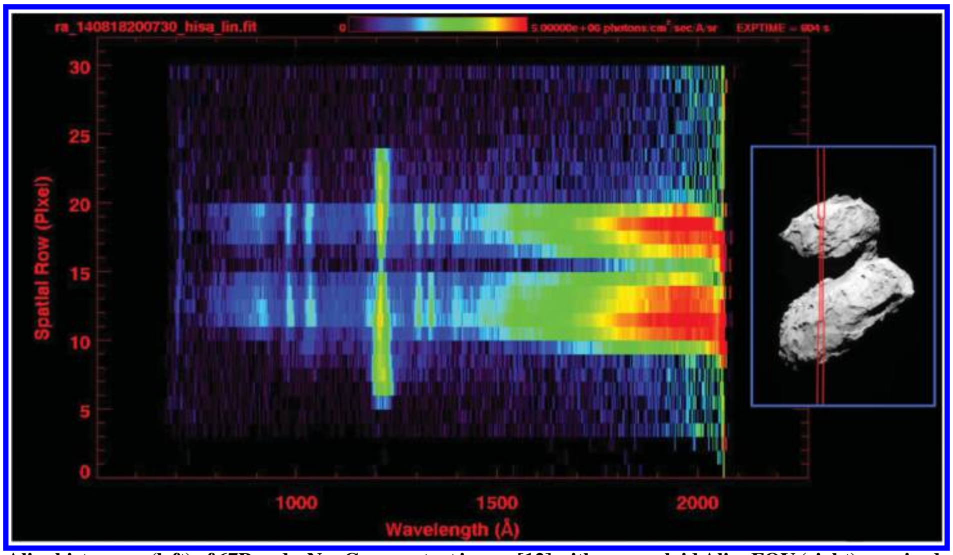


**Fig. 5 Example of an Alice histogram (left) of 67P and a NavCam context image [12] with an overlaid Alice FOV (right) acquired on 18 August 2014. The context image can help with identification of scene characteristics to correlate histogram features.**



Alice team used just the NavCam (NCIRs) for context imaging until 11 May 2016, when data volume constraints started to significantly increase. At that point, there was a transition to use OSIRIS WAC images (OCIRs), which could be compressed, saving a large amount of data volume to be repurposed as additional Alice science observations.

### H. High-Energy Electron Measurements

As a secondary science pursuit, Alice was periodically configured to measure the high-energy electron, or "HEET", component of the space environment. The Alice detector could sense penetrating electrons and would record them in the detector count rate data. This was accomplished at low data volume cost because the count rate was included in the Alice housekeeping data packet. HEET measurements were made with the Alice aperture door closed, the detector high voltage on, and at an elevated housekeeping sample rate of 1 Hz in an attempt to capture short-term electron density changes.

## V. Mission Planning and Product Development

### A. Mission Planning Coordination

At first glance, the prospect of balancing the needs of the 21 Rosetta mission instruments seems daunting, especially with each team based at separate institutions scattered across Europe and the United States in different time zones, and each team passionate about their anticipated science. Nonetheless, the mission was a resounding success and data were recorded to satisfy the Alice instrument science goals. This was achieved through tireless operations design, development, and planning support from all the instrument teams and the ESA science operations team [6,7]. Additionally, the freedom to self-harmonize science planning within the Rosetta science community instead of being directed by management led to holistically balanced and mutually agreeable solutions.

An observation importance hierarchy between instruments was not always clear because mission science goals were not requirements or ordered by priority. However, teams usually came to an agreement on their own when science priorities were made based on dataset uniqueness and continuity. Often, the teams made compromises to merge observation types for highly desired periods such as adding periodic stares during scans, adjusting scan rates and stare locations, etc. Fortunately, this task became more manageable because only a subset of instrument teams needed to actively participate in resource negotiations, including Alice, MIRO (Microwave Instrument for the Rosetta Orbiter), OSIRIS, ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis), RPC (Rosetta Plasma Consortium), VIRTIS, and sometimes the Philae lander team. The resources that the remaining instruments typically required were low enough that they were automatically granted or they were able to achieve their desired observations by riding along on the pointing designed by the other teams.

There were exceptions to the typical negotiation process, with the biggest being how to balance the potential resource needs of the Philae lander and its 10 instruments if and when it became functional again in the months after the landing. Sometimes, this led to resources and scheduling to search for the lander or to attempt to recover a lander signal taking priority over other Rosetta spacecraft plans. That, in turn, resulted in late changes to the trajectory to optimize communication and view opportunities, added multiple-case planning, drove additional pointing constraints, and required resources to be reserved. Unfortunately, among the many contact attempts, there were only brief additional contacts with Philae roughly seven and then eight months after landing (see Table 1 for the dates); the contacts were not sufficient to command extended additional lander science activities.

### B. Long-, Medium-, and Short-Term Planning Phases

Rosetta planning cycles were divided into three primary phases: long-term planning (LTP) managed by the RSGS liaison scientists [6]; and medium-, short-, and very short-term planning (MTP, STP, VSTP, respectively) managed by the RSGS operations and planning group [7]. Typically, an LTP period consisted of two to four 28-day MTP periods, which consisted of four one-week STP periods: each of which was divided into two VSTP periods [6,7]. Each instrument had its own master science plan that defined measurement goals, their relative importance, and the observation methods to accomplish them. These and other science goals were combined during the LTP with input from the science working team (instrument teams, interdisciplinary scientists, a trajectory and activity group, and cometary science topic discipline groups) and the ESA and NASA project scientists [6]. These high-level discussions looked at "Where do we go?"; i.e., types of orbits, flybys, excursions, etc., that would satisfy various science goals. This LTP-level work resulted in a draft trajectory and high-level observation plan. Then, in the MTP planning phase, each team would make requests for the needed resources, such as spacecraft pointing, data volume, power, and telecommand count. This was done with a resource and request tracking spreadsheet typically covering four weeks of operations, and it was subdivided into short blocks of time defining spacecraft activities or blocks available for instrument teams to request. This typically resulted in 3–4 h instrument observation blocks separated by 30–70 min spacecraft activity blocks that instrument observing might or might not need to avoid due to propulsion and nonoptimal pointing activities. Every observation block for the entire two-year encounter was reviewed and negotiated for by the instrument and spacecraft teams. Harmonization of plans took place with RSGS liaison scientists moderating the process from ESA's ESAC facility in Spain, whereas the various instrument teams dialed in from around the globe. Harmonizing the observation requests often took a lot of time and compromises, and they occasionally got heated when designs could not achieve everyone's needs. However, it was a testament to international collaboration and cooperation that most negotiations were attained smoothly and with enough time to implement. After harmonization, implementation of the MTP and leading to the STP was done in which the commanding products would be built, refined, and validated. Finally, there was opportunity for nonstandard or emergency activities and changes to be added at the STP and VSTP phases. This was the general structure of the planning process, but there were changes throughout the mission in response to adapting to the comet environment and needs by the science teams for planning closer to execution [6,7].

### C. Evolution of Operations Planning

During the first nine months of encounter, the cometary activity was low and the spacecraft orbital trajectory planning was very stable, excluding the various Philae landing scenarios. This allowed for long development process durations; for example, the LTP phase started six months before the execution of the planned activities, the MTP phase kicked off 2.5 months before execution, and there were several weeks for STP adjustments [6,7]. This led to concurrent planning of several MTP periods but plenty of time for planning each MTP. However, this luxury was short-lived because the comet became active and the orbital trajectory needed to be adjusted on a much shorter timeframe to keep a safe distance from the comet and particularly active areas, such as the comet neck and the side of the comet pointed to the Sun where the gas and dust densities were higher. Planning phases were highly compressed after this point [6,7], but the mission was able to maintain the ability to plan observations that correlated to specific comet phase angles, locations, and other characteristics, which resulted in much better formulated datasets when compared to arbitrary pointing scheduling.

The remaining 16 months of the mission planning proceeded at a frantic pace with the LTP phase starting two months before execution and the MTP and STP phases merged and kicked off a month before execution. Unfortunately, last minute changes to pointing at the STP level by other instrument teams were not rare and usually required a scramble to accommodate in the commanding for Alice and other instruments. However, the Alice team was appreciative for the opportunity to make STP-level changes to the pointing as well to optimize some observations, especially stellar appulses, which were discussed in the Alice Observation Types: Gas Observations section (Sec. IV.D). An additional challenge in several periods of the escort phase was that pointing had to be kept robust against late changes of trajectory [6,7].

The compression of the planning timeframe impacted all facets of operations from observation design, resource harmonization, implementation, development tools, product review timing, and product validation timing. It required that processes and systems be developed that could be efficient, adaptable, reliable, and modular. Among the Alice team, a wiki was used for efficient communication of product status and Subversion software was used for product version tracking. Modular Python, Perl, and bash scripts were used for product development and verification that allowed for quick adjustments and testing as mission inputs and formats changed and new capability was needed. ESA mission simulation models (including ESA's Mapping And Planning Payload Science (MAPPS) software [8]), Satellite Tool Kit scenarios, and an Alice engineering qualification model (EQM) were also used for product validation. A software testbed, spacecraft simulator, and EQM at Southwest Research Institute were used for isolated testing of some sequences; but, for high-fidelity testing of a command load, it was necessary to test on the Alice EQM unit that was mounted on the spacecraft model at ESA's ESOC facility in Darmstadt, Germany; because of the schedule and setup time constraints for running command loads on that spacecraft model, only unusual, critical Alice activities were tested on it.

## VI. Mission Perspectives

### A. Lessons Learned Summary

Cooperation, joint planning, and data sharing between teams led to better overall science. TOOs, context images, star calibrations, and other cases of correlating several instrument measurements led to a more complete understanding of the comet processes and observed scenes.

Transparency in the operations planning for all instrument teams helped with understanding each other's goals and helped make the harmonization process more efficient. This was achieved by documenting observing styles, labeling observations in a standardized way, and collecting observation requests in one place for side-by-side review and harmonizing.

It was essential to automate planning and commanding as much as possible to minimize manual effort, particularly for a long-term orbital mission in a constantly changing environment, as compared to a flyby mission. This led to more efficient planning and reduced operational risk. It was found that rolling out capability incrementally and using open-source software quickened the implementation of automation software. A recommendation for future Alice-like instruments would be to update flight software so it is flexible enough to create additional instrument sequences that combine sets of commands used regularly to reduce risk in building command loads, minimize command counts, and make operations development more efficient.

In terms of personnel, it was found that it was worth the resources to have someone who was working on operations development who had intimate familiarity with the systems and its needs and was provided with sufficient time to build and test operations tools to improve the process. Having operations personnel who worked full time on just that one mission was very important as compared to having operations engineers whose attention and time were fragmented by working multiple missions simultaneously.

There is strong value in having a liaison between the operations team and the science team who can help translate requirements, constraints, jargon, etc., between the two teams.

Having an instrument flexible in pointing (made possible with a large FOV and long exposure times) meant the Alice instrument could take advantage of observation blocks that were of little use to other instruments, giving Alice more prime pointing than it would have otherwise secured.

Implementing an ongoing process of assessing operational constraints and assumptions helped to identify areas to optimize. For instance, the gain sag rate was reassessed, resulting in adjustments in bad dog avoidance and ride-along observation planning.

The freedom to self-harmonize science planning within the Rosetta science community instead of using arbitrary scheduling or solutions directed by management led to holistically balanced solutions and additional collaborations, and not just compromises.

Being clear with communication and scheduling deadlines was very important to reduce issues for an international mission with team members spanning many time zones and native languages but requiring many weekly meetings for planning coordination and quick-turnaround responses. One area of communications that could be improved on Rosetta was that, occasionally, the ESA mission software used for product development and modeling would change without advance notice, which negatively impacted ongoing development because it would require changes to interface and development software in a very short timeframe. Better transparency into mission software changes before they were implemented would have reduced rush changes, software workarounds and rollbacks, and the risk of command errors.

Having mission-common visualization and resource tracking tools is important to provide a single frame of reference and common data products for all teams, facilitating compatible solutions to end-to-end operations development from observation design through implementation.

Participation in meetings is necessary for all teams that desire to have a voice in the decisions being made. Revisiting decisions because someone did not attend a meeting can waste a lot of people's time.

### B. Alice Logbook

For further Alice operational event details, please refer to the Rosetta Alice logbook that will be in the Rosetta Alice archive. It is a plain-text machine-readable simple-format file that contains details for Alice events, major spacecraft events, all observations by name and by date, and other information valuable to using and understanding Alice data.

## VII. Conclusions

Rosetta Alice was the first UV spectrograph to study a comet at close range. It successfully monitored gas and dust escaping from comet 67P/Churyumov-Gerasimenko, as well as the comet's surface properties throughout the encounter mission phase. The instrument was at risk for contamination and gain sag, and actions to minimize these effects drove many operational constraints for much of the encounter. Those and other changes to instrument performance during flight were accounted for by performing regular calibrations using bright UV stars. The design of instrument operations and comet observing techniques were performed in conjunction with several ESA groups and many other Rosetta instrument teams. Cooperation and joint planning between the teams fostered collaborations instead of just compromises and led to a more complete understanding of the comet processes and observed scenes.

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