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Cassini Distributed Instrument Operations – What We've Learned Since Saturn Orbit Insertion

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The Cassini mission to Saturn is complex with 12 science teams conducting distributed operations across the United States and Europe. Each Team includes scientists from around the world who actively participate in operations, including observation design, instrument commanding, downlink processing, and archiving. This represents a change in how JPL complex deep-space missions have been operated. Since Saturn Orbit Insertion (SOI), the Cassini Project has spent 17 months conducting science operations and has gained real-world experience that has tested the assumptions and rationale for this approach. We have learned that many of the expected benefits have been realized, but there were numerous unexpected challenges as well. This paper will discuss the lessons learned from the Cassini Tour experience to date. It will revisit the assumptions and rationale behind the distributed instrument operations design and will describe the results, good and bad, of implementing this method of operations. We will describe how Instrument Teams are structured, their roles and responsibilities, what challenges they faced going into orbital operations (the "tour") and what creative solutions were proposed when funding limitations and schedule milestones prevented optimum solutions. We will also discuss the problems that have been encountered both on the ground and with the instruments, how these problems and anomalies were overcome, and what was learned along the way about the characteristics of distributed instrument operations.

I. Introduction

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II. Cassini Instrument Operations Concept and Decision Rationale

Today the trend to perform instrument/science operations at a centralized science center – usually in a separate location remote from the mission operations facility, but this was not the approach taken by the Cassini Project. In the 1990s, the distributed instrument operations concept was just beginning and the Cassini Project decided to take that path. Cassini management decided that all work to fly each instrument could be performed at the home institution of the Principal Investigator. Therefore, the twelve instrument teams are physically located across the United States and Europe (see Figure 1 for instrument teams and their locations). The mission operations center is

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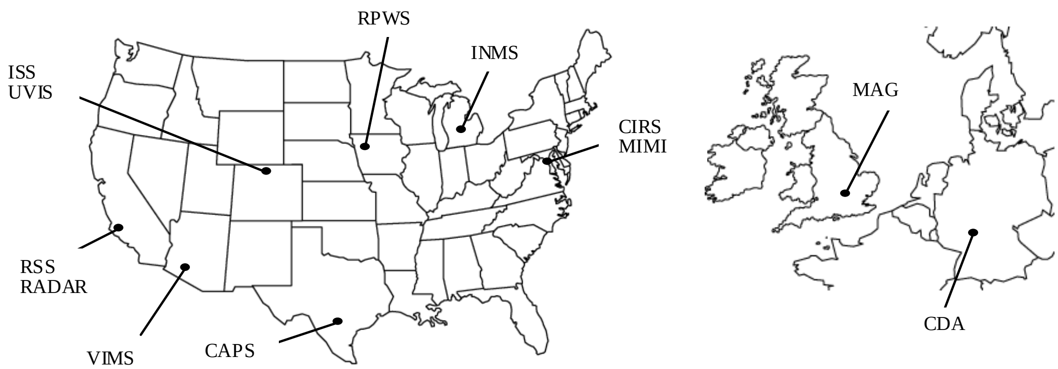
located at JPL. Of the 12 instrument teams, eight are remote, two are at JPL, and two are split between JPL and the PI institution (because the instruments were built by JPL). Two of the remote teams are in Europe.

When the decision to go with remote instrument operations was made, the only constraints placed on the instrument teams were to stay within their allocated budget and deliver their products on time as dictated by the Cassini Project schedule. The instrument teams were expected to devise their own ground system to perform their work, although two JPL Science Operations Planning Computers (SOPCs) were provided to each instrument team, with tools to help generate observation designs and stored sequences, and to monitor the health and safety of their instrument.

Among the reasons for going with the distributed instrument operations approach were:

- Cassini is a long mission with seven years of cruise, and four years of tour with the possibility of extended mission. Frequent travel or co-location would be costly.
- Distributed Operations would increase the probability of keeping instrument expertise around for the duration of the mission.
    - Flight software updates requires instrument expertise and this is a responsibility of each instrument team.

Instrument problems were more likely to occur in tour (after operating the instruments for seven years in cruise) and this is when instrument expertise and historical operating knowledge would be important.



CAPS	Cassini Plasma Spectrometer, *Southwest Research Institute, San Antonio, USA*
CDA	Cosmic Dust Analyzer, *Max Plank Institute f r Kemphysi, Heidelberg, Germany*
CIRS	Composite Infrared Spectrometer, *Goddard Space Flight Center, Greenbelt, USA*
ISS	Imaging Science Subsystem, *Space Science Institute, Boulder, USA*
INMS	Ion And Neutral Mass Spectrometer, *University of Michigan, Ann Arbor, USA*
MAG	Dual Technique Magnetometer, *Imperial College, London, UK*
MIMI	Magnetospheric Imagin g Instrument, *John Hopkins University, Baltimore, USA*
RADAR	RADAR, *Jet Propulsion Laboratory, Pasadena, USA*
RPWS	Radio And Plasma Wave Spectrometer, *University of IOWA, USA*
RSS	Radio Science Subsystem, *Jet Propulsion Laboratory, Pasadena, USA*
UVIS	Ultraviolet Imaging Spectrograph, *University of Colorado, Boulder, USA*
VIMS	Visible And Infrared Mapping Spectrometer, *University of Arizona, Tucson, USA*

Figure 1 – Cassini Instrument Team locations and related institutions

Other rationale lending itself toward the distributed operations approach included:

- During ATLO the instrument teams could begin using their JPL provided SOPCs, allowing more “expert eyes” to look at the data and thus reduce travel, saving the project development dollars. This also allowed the Project to follow the “test as you fly and fly as you test” paradigm.
- Instrument sequence development was going to be a challenge with so many instruments and no scan platform, so it was felt that since the instrument teams were the recipients of the science data, they could do the work to get it. The science team members on each instrument team liked this idea too because now they could be in greater control of what was requested.
- Cassini operations processes did not require quick turnaround, thus the remote factor was not as significant.

- Instrument operations cost could be controlled through Science Team contracts, thus the science team would have to live within their budget, with the non-compliance consequence being that they would not get their science.

The mission operations concept for gathering science data was to request, integrate, design and build the science observations into 41 sequence loads and put them on the shelf for update prior to execution. Processes were developed to support this work. This tour sequence development effort started approximately three years before orbit insertion and required the instrument teams to work on multiple sequence loads at the same time (overlapping in schedule). Each load of approximately 30-45 days could contain anywhere from ten to fifty observations for each instrument. At the beginning of tour development, two sequence development two loads were worked on at the same time, and as time became scarce, the number of simultaneous loads developed at the same time became as high as six. Cruise activities were also being developed and were executing at the same time. So going into Saturn Orbit insertion the instrument teams were strained to complete the first version of the tour.

Tour development follows an agreed to integrated activity plan, assigning time to each instrument. The integrated plan is documented on a unique Cassini web-based database (CIMS). The Cassini Project allows each instrument team to design their own unique observations by generating Instrument Expanded Blocks (a set of instrument commands) that together with the pointing vectors (spacecraft attitude) define an observation. The observation must stay within its resources (data volume allocation) and must comply with all flight rules. Each observation is designed by the prime instrument team and can accommodate rider instruments. The rider instrument teams define their observation commands using the prime instrument provided pointing vectors. When pointing changes are made via a Sequence Change Request, the new pointing vectors are put on a special FTP website and the rider teams are notified via email (prior to the Change meeting) so they can evaluate the change and voice an opinion at the Sequence Change meeting. Meetings are primarily teleconferenced. At this point in the mission instrument team members are recognized by their voices.

III. The Cassini Instruments

Cassini's 12 instruments are divided into three groups according to their science objectives. The first group is the Magnetosphere and Plasma Science (MAPS) instruments. The MAPS instruments include CAPS, CDA, INMS, MAG, MIMI, and RPWS. The MAPS instruments need full sky coverage to achieve their science goals and for the most they request that the S/C roll during the daily nine hour downlink and ride on other instrument activities by requesting particular secondary axes. The second group is the Optical Remote Sensing (ORS) instruments. The ORS instruments include CIRS, ISS, UVIS, and VIMS. These instruments are bore-sited and require precise pointing to achieve their science objectives. The last group is the Microwave Sensing instruments - Radar and RSS. Both instruments are not bore-sighted with the other instruments, but view from the –Z axis. Both microwave sensing instruments require precise pointing to achieve their scientific goals. The RSS Team uses the Deep Space Network antennas and Spacecraft telecom system as their instrument. Figure 1 below depicts the locations of all instruments on the Cassini Spacecraft.

IV. Surprises Found During the First Year of Tour

Exploring a new planetary system always provides surprises. Some were because of Saturn system unknowns and some were operational. All of these surprises required work by the flight team to solve and each affected one or more instruments and their teams.

- Titan's atmosphere was denser and more uncertain (variable in latitude) than had been predicted using models from Voyager flyby data. The 950 kilometer (km) planned Titan flyby altitude had to be raised between 10 to 80 kilometers for twenty one of the twenty four Titan flybys. The structured processes set up for instrument science integration and sequence updates allowed all instrument teams to assess the impact of the trajectory changes on their activities. Note: a JPL engineer generated all of the science pointing plots and provided them to the instrument teams, so being remote did not really affect the ability to analyze the situation.
- The thermal environment at Saturn turned out to be a lot colder than models predicted. The UVIS instrument was found to be approximately four times more sensitivity in its long wavelength than it was at launch. This is not understood.

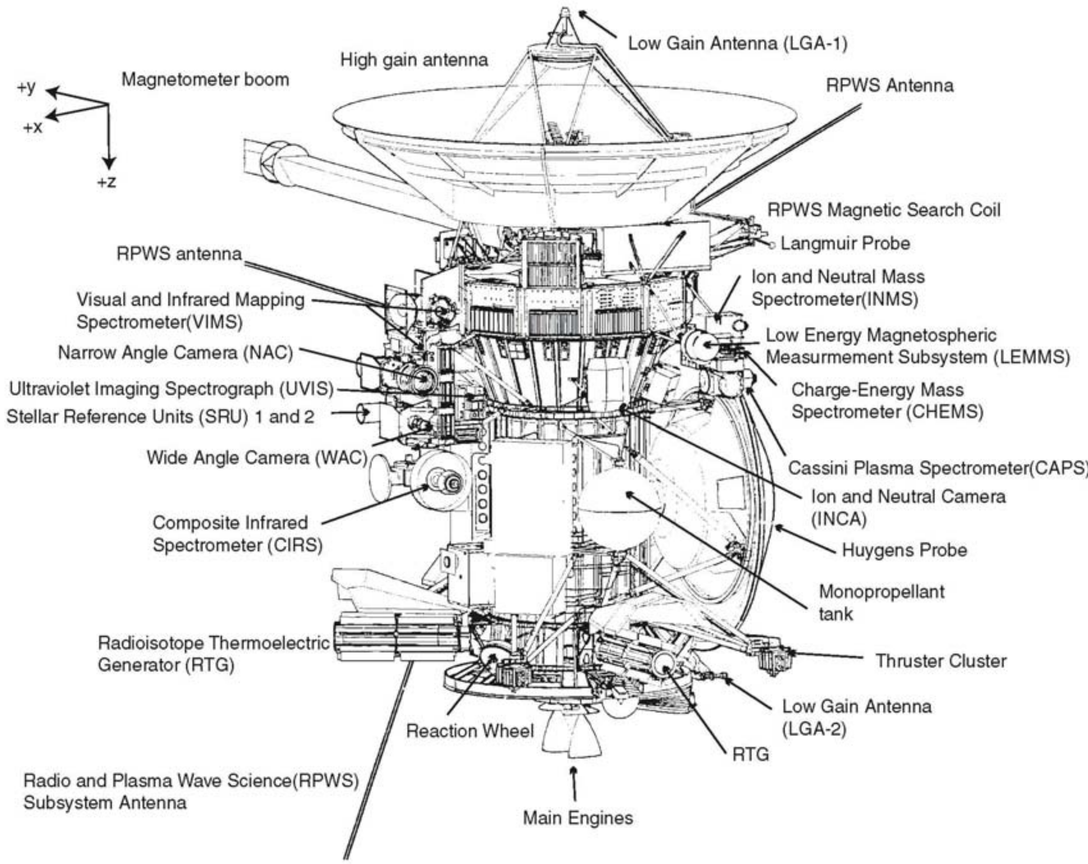


Figure 2 – The Cassini Spacecraft with instrument payload. (Note: CDA and RADAR are not shown on this picture)

- The Cassini version of the Bus Interface Unit which allows for two way communication between the instruments and spacecraft has a bug, which impacts instruments when there is heavy communication traffic. The full effect of this software bug was not seen until tour. The bug has caused instrument resets and transmitted commands not to be received by the instrument. The instruments affected used their flight software to solve this problem. The additional instrument team work required to resolve this problem was significant and unexpected.
- Two instruments were found to be sensitive to high reaction wheel speeds. Since the spacecraft movement (instrument pointing) is primarily controlled by these reaction wheels, this is a problem. Mechanical interference is seen in the CIRS science data, and RPWS can tell when the wheels are healthy (less noise is seen). Resolution of the CIRS problem required a lot of interaction with the Spacecraft Team, and an additional sub-process (to keep reaction wheel speed low). Because the CIRS team was remote made this more difficult to solve, primarily because a new process had to be developed that took into account the affect of this change on other instrument's activities.
- Instrument to instrument interference in flight was found, but not seen during ground testing. (MIMI now turns their high voltage down for a period, then ramps it back up and this appears to resolve the interference with RPWS.) This is remote team to remote team interaction which works fine.
- When we arrived at the SOI, the Radio Science Team had not yet figured out how to perform their limb tracking maneuvers (required to perform occultations), as the spacecraft was not built to move that quickly. This was a huge problem. Varied expertise was required to solve this problem – including the

key AACS initial vector propagation developer from 20 years ago, and other spacecraft experts, programmers who understood celestial mechanics, and radio science team members. Face-to-face meetings weekly for years were needed before a solution was found. It was highly advantageous that the Radio Science Team was at JPL.

- As part of the sequence adaptability strategy, we know that with long sequences and long lead times for sequence production we would need the ability to do live updates for observation of the executing sequence. The "Live Update" process was devised as a scheme to react to late breaking knowledge where target locations had changed. Doing a sophisticated statistical study the Project predicted fifty to seventy five live updates might be needed for the entire tour. Today Navigation predicts are so spot on that live updates are rarely needed.
- Since the Instrument team staffing was not robust, some of the Science Co-Investigators were called upon to design observations the team had requested. (This occurred on the three instrument teams.) This meant the Instrument Team re-distributed some of the ops work to further remote sites (some in Europe). These Co-Investigators had to be provided with a capable computer, planning tools, training (to run the programs), input files needed to generate the designs, and the schedule to complete the work. Training remote teams to use the JPL provided tools is a challenge.
- The Ops team discovered that the pointing design tool that provides the option to track a ring gap azimuthally around the planet generated so many commands the az scan did not fit into the on-board allocated sequence space. The tool is currently being fixed by the software team and will be delivered soon. The imaging team lead operations engineer came to JPL to test the tool's new capability and train on the tool prior to delivery, so some additional interaction was required because the team was remote.
- Some instruments experienced operational problems. The problems have been with "moving parts" not moving correctly. The CAPS instrument actuator didn't move as commanded, so flight software was used to change the commanding method. The MIMI Low Energy Mass Spectometer (LEMMS) stopped rotating 360 degrees. The MIMI instrument Team moved the LEMMS to a pitch angle that provides the most useful data. Rather ironically the CDA high rate dust detector was impacted by a large ring particle (currently being evaluated for a solution). The Vector Helium Magnetometer is currently in an anomalous state that is not understood. Investigation is underway to figure out what to do. The fact that the teams were remote really doesn't seem to have made a difference when problems are internal to an instrument.

V. Areas where Challenges Exist

Tour is very intense compared to cruise. There are more meetings that require Distributed Operations Teams attention. Cassini could no longer fit all of the needed meetings into morning time slots. Our partners, especially in Europe, ended up working all hours of the evening to support meetings for west coast day-to-day operations. JPL Investigative Scientists were provided to each instrument team to represent each team's interests in planning & implementation meetings. This did help, but the very remote teams (in Europe where the time difference is 9 hours) have found that if one team member works 2^{nd} shift, the meetings can be accommodated. This does put a burden on those teams.

Communication is the single more important challenge with remote sites. Cassini communications are primarily through email and teleconferencing. This means of communication is not as effective as being co-located. Also when several teams are involved in solving an anomaly, or working an issue, communication is not as good if team members don't knows each other. Project Science Group meetings twice a year (one in the U.S. and one in Europe) do help personnel get to know each other.

IT Security requirements at JPL have been continually increasing to protect our systems against those who want to inflict harm. The project is constantly updating networks and SOPCs to tighten security. Sometimes changes have been implemented so quickly that Cassini's distributed sites do not receive adequate warning, and at times have been unable to connect to a Cassini secured server or to some of the other secured site at JPL. This is also because the Cassini project is using multi-mission software on multi-missions networks, so if another project needs an immediate update/reboot, it just happens.

Being a remote Instrument team means you can be ignored when problems aren't urgent. The old saying holds true – out of sight, out of mind. Being remote means you have to be vocal and persistent when you need assistance or attention.

VI. Improvements Made Post SOI (i.e. Creative Solutions)

Working instrument operations with fewer people than are really needed to get the job done presents many challenges. Shown below are some of the interesting ways in which the Cassini Project and the teams responded to this challenge.

- When the "Crunch" period hit, here is what some of the teams advocated:
  - Use free student interns. (Hire and train high school and college students to assist in observation design. One instrument team hired Oxford students (Co-I was at Oxford), trained them at Oxford, and then during the summer sent them to Goddard to work, starting their first day fully trained on the Cassini tools. These students worked several summers.)
  - Look at the skill set of the engineers and match the job to the need.
  - Offload work to scientists (Co-Investigators)
  - Work lots of hours
  - Limit the number of changes (don't fix everything, just the most important things)
  - Develop tools to catch most of the probable error prone areas.
  - Accept "good enough" vs. "perfectly accurate".
- The Pointing Design Tool (PDT) on Cassini operates very slow on the Ultra 10 workstation (the Cassini provided workstation). When the project went with overlapping sequence development, the Instrument Teams had trouble keeping up. After SOI, the Project developed a client/server version of PDT (which increased processing speed by 50%). The code was ported to Linux so a PC/MAC could be used as a client. The graphics could be plotted on the Ultra 10 workstation, but the number crunching could be done by the significantly faster PC processor. This helped the instrument teams increase productivity. The fact that the teams were remote had no bearing on this particular solution.
- To ensure that the remote teams used the correct input files to design their science observations, the Project developed a script which pulled the correct input files as identified per sequence and loaded them into the software. This solved the problem of the remote team typing in the wrong file name and grabbing the wrong files/s.
- Trades were made on both instrument teams and JPL Ops teams to off-load work. The Project developed what is called- ASP (automated sequence processor) in which command requests are automatically generated and sent to the real-time ops engineer on console for uplink to the instrument. Only non-interactive instrument commands can be used. This saves the rest of the team from attending coordination meetings and it's quick (the entire command generation takes minutes).
- Cassini built an archive tracking tool called CATS (Cassini Archive Tracking System). This tool has a nice easy interface for the instrument teams to status their archive data, once its delivered. The tool is web-based and was built to automatically generate status reports. The Cassini tool was built for multi-mission use and is being picked up by new missions.
- One of the European Teams built a virtual Ada compiler – on a PC. This has allowed the instrument team to develop their flight software from any location (home, on travel, etc) – Details are provided in Stephan's paper (add reference detail).
- The European CDA Team developed the ability to remotely set up their instrument testbed in Heidelberg while at JPL (or another remote location), run a test, look at the status of the test as it runs and look at the data from a PC. This is a valuable capability to have for an instrument team that travels a lot but still needs to participate in operations. Refer to Stephan's paper (in German)
- For information exchange and distribution of data between Distributed Ops sites and JPL, the Project uses SSL encrypted proxy and web servers, and LDAP. Instrument Teams (whether Foreign National or not) work on the same network, called the Cassini Science Users Network. Instrument Team members bring laptops to JPL with their own software installed and connect to this secured network (which enables everyone on the project to exchange the information).
- Post SOI the Cassini Project built test-beds to match the operational configurations of the Distributed Ops sites (to the greatest extent possible). In reality this is more difficult than it sounds. Distributed sites have institutional firewalls, security restricted resources, etc. that differ greatly site-to-site, country-to-country. This way when upgrades to the instrument SOPCs are made, the Project know they will work. This is currently a work in progress, and not 100% complete.
- The Cassini project originally leased dedicated data lines connecting all of our distributed sites with JPL (serial 56K bandwidth lines). The dedicated lines (especially overseas) were very expensive. The cost in 2002 for example was: $41K for domestic and 254K for international lines. Last year Cassini moved to the Virtual

Private Network (VPN) over the internet. This technology advancement has reduced the cost of distributed operations and provided a secure connection and increased bandwidth.

VII. Project Lessons Learned

The Cassini mission has been flying for a long time now, almost 9 years and has a lot of experience in complex instrument operations. The lessons learned below are Project lessons learned that affected one or more instrument team.

- Just because your instrument for has been flying a long time (7 years for Cassini) does not mean that flight software is adequate for complex tour instrument operations. It's advisable to have some flight software maintenance in the budget for the prime mission. The flight software programmer can be given other operational tasks to ensure he/she stays on the team.
- Don't freeze your ground software for a long period of time when a new phase begins – The Tour Ops Readiness Review board recommended that ground and flight software be frozen for one year after SOI (so as to not incur any risk with the Titan Lander to orbiter relay). This ended up being a bigger problem than one would have expected because the command data system flight software was delivered right before the freeze, and after it went operational there were some instrument data return issues that could not be fixed for a year (the VIMS team couldn't tell when they were data-policed and the radar team didn't get thermal information anymore). This cost instrument teams one year in additional ground work-around. A short freeze of several months prior to the Titan landing would have been sufficient. The other lesson here is to coordinate spacecraft flight software upgrades with the instrument teams to let them know what changes are being made. Because the teams were remote, it was easy to forget that they could be impacted.
- One good test is worth 1,000 expert opinions – especially when it comes to 1st time events. Cassini lost a prime science opportunity for one instrument post SOI because the instrument turn-on was at the wrong time. The project was so concerned about orbit insertion (which was tested every way possible) that the following unique science period was not simulated. The remote site did not have room in their schedule to run the sequence through the testbed so it didn't happen.
- Formalize Roles & Responsibilities Agreements early with distributed instrument sites to localize change control and limit change authority on SOPCs to a single JPL group managing all remote and local SOPCs. Each site has a System Administrator – but it is agreed their role is limited and no change is made to the core SOPC configuration except by JPL (the SOPC provider).
- When the schedule is put on fast-forward to accommodate work not complete (i.e. tour), project personnel need to remember to go back and evaluate whether the tools and resources supporting the effort are adequate. This was not done on Cassini when the instrument teams had to work on six sequence loads concurrently (called the "crunch period). The PDT tool used to design observations was woefully slow.
- A small team of ground system experts dedicated to working remote instrument team interface/data flow problems is needed at the mission operations center. There are breakdowns that continually plague the remote instrument teams and they need a voice (and problem solver) at the prime mission ops site. Cassini has a small team of two engineers that overlap their schedule (working 12 hours/day) to meet the daily needs of the remote teams.
- Be aware that Security requirements will continue to be imposed at all phases of the mission. In the current extremely sensitive security environment Projects are expected to implement new requirements immediately, but additional funding is never provided. Also, these "new requirements" don't go thru the normal Project Change Processes so mission operations is never able to impact the required change, cost it, or reject it; we simply must make it happen now, with no added money and no slip in schedule. This problem just propagates to the instrument teams who are on the receiving end of the changes.
- On a long mission like Cassini, plan for and commit to making incremental changes in hardware and software which utilize new/better technologies as they become available. It is impossible in an eleven year mission to design a ground data system, develop it and then assume it will never change or need to be replaced until the end of mission. Sustaining maintenance should be embraced. Somehow developers should stick around (perhaps in OPS roles but still able to continue ongoing technology improvements thru the life of the mission). Staunch, controlling Configuration Management types won't do – for a long mission, "plan for change" and have GDS Engineers able to embrace change (while still managing – which is the challenge) and "engineer-in" the needed incremental improvements.

- Don’t be afraid to fully document everything – changes, thoughts and reasoning, limiting/controlling factors, failures and causes. There will be high turn over in a long mission, reasons will be forgotten, you must be able to reconstruct how you got where you are now whether you were around when the decisions where made or not. What looks like a bad decision in retrospect might have been the only feasible decision for the time, given the circumstances – documenting that will be important.
- Practice, Practice, Practice. Start readiness testing early (must simulate OPS configuration and conditions) to uncover problems early (Probe operational readiness tests before Probe Release exposed the fact that the Project did not have enough bandwidth in the 56K NISN line to the Huygens Probe Operations Center (at ESA) and we replaced it with a 128K line (which cost quite a bit more).
- Exploit to the greatest extent possible effective Information Sharing techniques: AFS, Web. Automate data distribution (FEI for example). Tools must survive common and regular internet interruptions, firewall timeouts, and various other security limitations without manual intervention or baby sitting – the data just needs to arrive when it should - lights out.
- Build and maintain Test beds and operational readiness tests that adequately simulate operations for the life of the project (not just in dev/test phase) – but they cost money to build and maintain.
- When developing data products, look at what is required for data archival and build the products to meet the required Planetary Data System format. This will save time, energy and money for everyone.
- Regarding change management of distributed operations sites - Test every configuration change, security patch, software installation, router upgrade and OS upgrade before pushing out to the distributed sites.

VIII. Best Advice from One Remote Instrument Team to Another (based on Cassini Experience)

- Automate as much as possible so the team can concentrate on the real issues and not everyday tasks. The RPWS team developed a tool that converts the time-ordered-listing from CIMS into a set of SEQGEN requests, and another tool that generates data volume. Note: The Project should have provided this tool.
- For teams that are time zones away from the operations center, have adequate funding to maintain sufficient manpower to adjust to crunches, vacations, illnesses, and travel.
- Cross train your entire team such that each person is capable of handling all aspect of operations.
- SPICE knowledge is critical if your instrument has to deal with pointing.
- Make sure your Ops people understand the commitment and can handle the stresses.
- Do not allow the Mission Operations to make you adopt internal requirements – just meet their interface requirements.
- Design your instrument to have internal science data storage and the ability to trickle the data out in your own housekeeping packets. (This also means there has to be an allocation in the housekeeping packets for science data.).
- Make sure the instrument ops budget has enough workforce to support the science integration schedule because no support to this effort means the team has to try and force their activities into the timeline after all the work is done.

IX. Summary

In summary, Distributed Operations can work and when compared to the option of co-location for many teams. It can be cost effective and work to the Projects advantage. If the remote sites are not in the United States, a technical assistance agreement must be approved so the Project knows what it can/cannot provide to the “non-US site” instrument team and the interaction is positive.

Communications is historically the challenge and continues to be a large hurdle to overcome. Recommendations to make communications easier are to provide a part-time Instrument Engineer located with the Mission Operations team. This person is the advocate for the distributed operations instrument team and a voice of support for their science when issues arise. Another avenue for assisting in communications is to continue to provide training and re-training throughout the mission. Training is very important and is not an area to save money in your budget. Train and cross-train throughout the mission both from the mission operations base and also personally at each distributed site. For Cassini, the continued bi-annual Project Science Group meetings between the distributed teams and the mission operations teams works well. It also serves as a mechanism for everyone to hear the latest science results.

Last, providing a common tool suite that is used across all distributed operations sites and across multiple platforms helps ease the burden of training and allows the sites to run these tools in their home environment, even from travel location or home.

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References

[1]Helfert, Stephan's paper…….
[2]LaValee, David, B., and Turner, F. Scott, "Automating Cassini Instrument Commanding for Saturn Exploration", IEEEE…
Note: need to refer to MIMI's work in paper

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