Conceptual Inquiry of the Space Shuttle and International Space Station GNC Flight Controllers

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14 March 2007

The opinions presented in this paper are my own and do not necessarily represent those of NASA.

Mission Control Center (MCC) Background

The concept of Mission Control was envisioned by Christopher Columbus Kraft in the 1960's. Instructed to figure out how to operate human space flight safely, Kraft envisioned a room of sub-system experts troubleshooting problems and supporting nominal flight activities under the guidance of one Flight Director who is responsible for the success of the mission. To facilitate clear communication, MCC communicates with the crew through a Capsule Communicator (CAPCOM) who is an astronaut themselves. Gemini 4 was the first mission to be supported by such a MCC and successfully completed the first American EVA [1].

The "MCC" seen on television is called the Flight Control Room (FCR, pronounced "ficker") or otherwise known as the "front room." While this room is the most visible aspect, it is a very small component of the entire control center. The Shuttle FCR is known as the White FCR (WFCR) and Station's as FCR-1. (FCR-1 was actually the first FCR built at JSC which was used through the Gemini, Apollo and Shuttle programs until the WFCR was completed in 1992. Afterwards FCR-1 was refurbished first for the Life Sciences Center and then for the ISS in 2006.)

Along with supporting the Flight Director, each FCR operator is also the supervisor for usually two or three support personnel in a back room called the Multi-Purpose Support Room (MPSR, pronounced “mipser”). MPSR operators are more deeply focused on their specific subsystems and have the responsible to analyze patterns, and diagnose and assess consequences of faults. The White MPSR (WMPSR) operators are always present for Shuttle operations; however, ISS FCR controllers only have support from their Blue MPSR (BMPSR) while the Shuttle is docked and during critical operations. Since ISS operates 24-7, the FCR team reduces to a much smaller “Gemini” team of 4-5 operators for night and weekend shifts when the crew is off-duty.

The FCR is also supported by the Mission Evaluation Room (MER) which is a collection of contractor engineers who provide analysis and long-term troubleshooting support. Each MER operator is an expert in a very small portion of a sub-system and each FCR console usually interfaces with several MER positions.

Contextual Inquiries

The goal of a contextual inquiry is to gain a better understanding of a subject, their work tasks and their environment by actually going to where they work and observing them. Unlike ethnography, which in the strictest form champions an un-interrupting silent observer, contextual inquiry encourages a mentor/mentee relationship which can help a designer more quickly better understand the needs of their subject. The benefit of a contextual inquiry is that the researcher can observe and question a subject while they are immersed in their work. Unlike an interview method, the subject does not have to try to recall how they carry out their tasks. All they have to do for a contextual inquiry is explain what they are doing as they do it. If the observer has adopted a mentor/mentee relationship, then they can probe with questions to help gain a full understanding of the subject's task [2].

The following discussion is the result of a contextual inquiry for a WMPSR Guidance Navigation and Control (GNC) Support Officer and their ISS BMPSR counterparts, HAwKI. The call sign "HAwKI" is derived from the fundamental concepts of their position's responsibilities: Momentum (H), Attitude (A), Angular Rate (w), Kinetic Energy (K) and Moment of Inertia (I). GNC Support's corresponding FCR position is called "GNC" and HAwKI's is ADCO (Attitude Determination and Control Officer). The MPSR operators perform most their subsystem's standard operation tasks including analysis computations, building and sending commands, documentation and research. Since the MPSR performs these tasks, the FCR operator is available to focus on integration with the other members of the flight control team. Thus, ISS and SSP MCC operations are more different at the MPSR level than the FCR level.

In order to perform the contextual inquiries I shadowed a GNC and HAwKI operator during two separate training sessions of a simulated Shuttle docking with ISS. The docking phase is the most intense orbit mission timeframe for both GNC and ADCO and is also the mission phase requiring the most integration with other systems. Each operator was "certified," meaning they have completed all training requirements for their position and each has previous real-time mission experience. For comparison with ISS, only the orbit mission phase of the shuttle was considered. For reference, the reader should note that GNC Support only works the orbit phase. During ascent and entry, GNC is supported by two MPSR operators: Control and Sensors.

GNC Support

The SSP GNC console is responsible for all the hardware that provides input to the guidance, navigation and control software and controls the vehicle. GNC system responsibilities include the inertial measurement units (IMU), engine trust vector controllers, accelerometer assemblies, digital auto pilot (DAP) software, rate gyro sensors, aerosurface actuators, hand controllers, star trackers, TACANs, microwave landing system, radar altimeters, trajectory control sensor (TCS) and Global Positioning System (GPS) receivers.

"Artifacts" are tangible things created for use or aids to accomplish work. [3]. An artifact model depicting a physical representation of the GNC support console is shown in Figure 1.

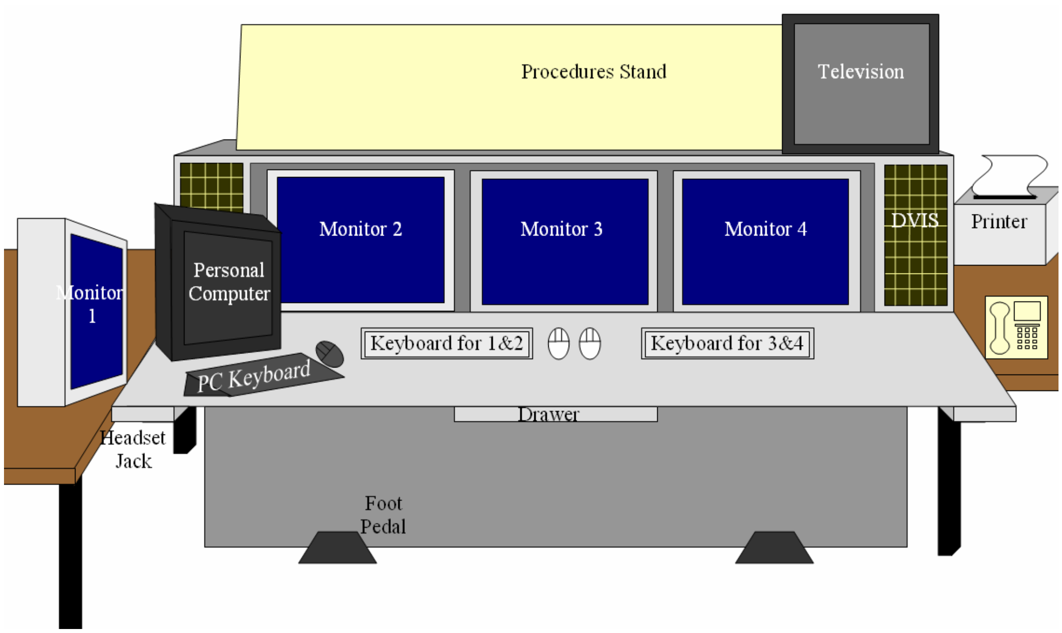

Figure 1. Artifact Model for GNC Support depicting a physical representation of the console setup.

The primary feature of the GNC support console are four monitors which connect to the SSP GNC server which are part of the larger MCC network. On these four monitors, the operator can arrange the digital telemetry displays as they desire, however, most operators set up their configurations similarly due to common training.

Monitor 3 is the prime monitor which is used to display the prime GNC Orbit high-density display (Figure 2). This display has high level telemetry from the prime orbit hardware systems including the orbital main engine system (OMS) TVC, IMUs, DAP, star trackers and an attitude summary.

Figure 2. GNC Orbit main telemetry display from a simulation.

From the GNC Orbit display, the operator can access more detailed telemetry from the various systems by clicking on the corresponding buttons. Under the IMU section, the buttons labeled “1”, “2”, “3”, “RSTRT DRIFT” and “RSTRT ACCEL” run computation programs to help the operator identify the subtle failure modes of the IMU hardware. The numbered buttons resolve the IMU attitude and velocity telemetry into the reference frames of each IMU and the DRIFT and ACCEL buttons restart an integrated calculation which is used to identify a drifting IMU platform, biases and scale factors.

The organization of the GNC Orbit display shows that GNC operators view their system as an organization of hardware components. Each display (or portion of a display) is dedicated to a specific sub-system. The benefit of this organization is that no matter how the hardware is being used and regardless of the current task, the flight controller can look in the same place for sub-system information. The main display also shows which sub-systems GNC operators view as the most critical since several hardware components have no telemetry on this display. The center of the display is the DAP since it is important that control of the vehicle is always maintained. This is indicative of the GNC console troubleshooting strategy to always make sure you have control, then troubleshoot problems. The largest portion of the display is IMU information which requires a substantial portion of the operator's awareness due to the subsystem's importance and many subtle failure modes of the hardware. The display is also organized with navigation aids and sensors on the right, guidance indications in the middle and control hardware on the left.

The information placed on the GNC Orbit display represents high-level indications from the sub-systems providing the operator with an overview of the hardware's performance. Should any of this telemetry indicate a problem, the operator would open a more detailed display for the hardware. Grouping the most descriptive, high level telemetry items on a single display allows the operator to gather overall system awareness with a relatively short scan pattern.

The display also contains the specific vehicle identification number, mission number, mission elapsed time (MET, time since lift off) and GMT. This enables hardcopies of the display to be tracked to specific events of a given flight and aids with documentation.

The structure of GNC displays is very simplistic since they were originally designed for significantly less capable computers. When the SSP upgraded to the WFCR, the display format was not changed to prevent having to retrain flight controllers. The black background with light colored text also makes the displays look like the original displays.

According to Bainbridge, “it is impossible for even a highly motivated human being to maintain effective visual attention towards a source of information on which very little happens, for more than about half an hour” [4]. Nominally during a mission there are frequent long periods of little activity for the GNC system especially during crew sleep, when the ISS is in attitude control and during robotic and EVA operations when GNC systems do not change configuration often. To aid the operator’s monitoring function, GNC runs several programs to help identify failures. Limit manager programs change the color of telemetry on the display when it exceeds predetermined bounds. Telemetry from units powered off or in “standby” mode are grayed out or made purple to not distract attention from operator. This colorization also causes a significant change when a unit power fails to drawn the operator’s attention to the failure. Many alert messages are also accompanied by alert tones in the headset.

To aid monitoring of the telemetry stream, GNC also has an automated events monitor called ELOG which creates a running log of events. Most operators place this display directly below the GNC Orbit display on Monitor 3. ELOG looks for pre-determined events in the telemetry stream and enunciates messages that these events have happened. For example, when the crew places the Shuttle into an inertial (INRTL) attitude hold ELOG will display a "DAP INTRL" message for the operator. ELOG is also used as a GNC events record for an entire mission. With each message enunciation the MET and the GMT time is recorded. The limitation of ELOG is that it only enunciates events for which it has been preprogrammed to recognize.

Next to ELOG on Monitor 3, the onboard fault summary (OFS) is displayed which keeps a running record of fault messages enunciated onboard. Some of these messages are nominal, for example messages generated as the crew powers on and off equipment. ELOG messages capture many more events than the OFS messages enunciated for the crew since ELOG looks for very specific GNC related actions.

"RT Plots" are placed on Monitor 4 which show selected telemetry items on graphs which scroll with time. The operator can add limit lines to these graphs, scroll backwards to see previous trends and events and add prediction lines. The most commonly graphed telemetry are attitude rates, deadbands, IMU telemetry and drift and OMS TVC gimbal positions to monitor control during on orbit burns.

Monitor 1 is also most often used for RT plots to monitor the control phase planes of the shuttle DAP. The use of Monitor 1, however, varies during the orbit phase. During rendezvous, it is used to display TCS information. While docked with station, it is used to for ADCO displays since most often the ISS is in attitude control and the majority of GNC's hardware is not being actively used.

Monitor 2 is used to run a program called "CRANS" which is a series of 100+ lights that turn various colors for different events. For example, if the main (MN) bus A of the shuttle failed, all the corresponding MN A box lights would turn red. CRANS also shows when any of the Shuttles RCS jets are firing. Monitor 2 is also used to display a series of clocks which count down to upcoming events and display GMT and MET time. Finally, a star tracker field of view graph is commonly placed on Monitor 2 to watch the star tracker's internal camera lock on stars and track them across the sky.

The GNC operators can also run several analysis programs on the console workstation which decrease the number of hand calculations they must perform to minimize human error. For example, one program converts attitudes into different reference frames, another determines which stars will be visible by the Shuttle's star trackers during a specified orbit. The workstation also has several applications which generate command loads that can be uplinked to the vehicle. These are discussed in greater detail below. Finally, through the workstations the FCR and MPSR operators can send screenshots of data to each other and view the same workstation documents, such as command loads.

The primary means of communication in MCC is through headsets. The use of headsets decreases ambient noise and allows communication between consoles which are located all around the MCC complex. The operator's headset plugs into either headset jack at the ends of the console desk. The Digital Voice Intercom Subsystem (DVIS) panels on either end of the console are used to select which loops the operator is listening to and which loop the operator is enabled to talk on. Some loops, such as the "air-to-ground" which is the loop for the CAPCOM and the crew talk to each other, can only be monitored by other flight controllers. The DVIS panel allows an operator to monitor up to 24 loops at time, however, on average GNC support monitors approximately 10 loops.

The operator can talk on a loop by depressing a switch on their headset or by pressing down on a foot pedal. The use of communication loops is further discussed below.

The personal computer is a Microsoft Windows PC which is used for e-mail, typing up shift handover reports, generating official “Flight Notes” messages for the rest of the control team, creating anomaly reports (ARs) which officially document in-flight problems and writing CHITS which is the formal documentation for communications between the operations and engineering teams. On the PC, the operator can also view JEDI (Joint Execute Package Development and Integration) messages which are electronic documents uplinked to the crew. These messages include flight plan updates, procedures and summary information.

TCS is an unusual hardware since it is not formally integrated into the Shuttle. Instead, TCS runs from a Window’s laptop in the Shuttle middeck and its telemetry is brought down along with the payload data instead of through the main telemetry streams. As such, GNC Support has the capability to run a ground version of the TCS command software on their PC. The ground copy of the software displays the real-time telemetry the crew is viewing onboard with their laptop, however, the ground software can only monitor telemetry and cannot generate TCS commands.

The television is used to view MCC closed-circuit video of the FCR and downlinked video from the Shuttle and ISS. The television is also used to monitor real-time position plots such as relative motion plots of the ISS and Shuttle during rendezvous. Placing these videos and plots on the closed-circuit TV system allows access to all MCC operators without taking up valuable workstation resources. Downlinked videos also provide operators with increased situational awareness especially during extra-vehicular activities (EVAs, or space walks) and robotic operations.

The GNC MPSR consoles are the only consoles to have a procedure stand. These stands were built by members of the group to hold up binders of procedures. They provide a convenient place to put procedures which can be viewed by the operator. The console desk has a sheet of plexiglass which covers many quick reference aids. These aids are notes made by the group for commonly referenced information. The procedures stands and plexiglass are two ways in which GNC flight controllers have modified their environment to assist with there job.

There are approximately 20 binders of procedures (called Flight Data File (FDF)) and over 30 binders of reference information located behind the GNC Support console. The procedures are organized by flight phase and intention. For example, there are binders specifically for ascent, entry and orbit operations. Each mission phase has a nominal operations book, a malfunctions book and a "pocket" which is for time critical off-nominal procedures. There are also procedures books specifically for EVA, rendezvous, robotic operations, the mission timeline ("flight plan") and on-board reference manuals. An example of a SSP flight plan page from STS-115 is shown in Figure 3. From looking at the flight plan, controllers can determine if scheduled activities will occur during orbital day or night, which crew member will perform the activities, the attitude and if there will be clear communication with the vehicle. Among these binders are hardcopies of previous post-flight mission reports, detailed description of the onboard software, reference schematics called SSSH (the Space Shuttle Systems Handbook), system briefs and standard console procedures (SCPs) which document step-by-step instructions for the operation of the console. Each console also has a hard copy of the program flight rules which document predetermined responses for various on orbit events.

At the end of a busy mission phase, the console often looks like an explosion of paper and binders with procedures opened to various pages and spread all over the console. With procedures in one book often referencing another and all the references and procedures required for nominal operation, the operator can quickly find themselves in several different FDF books at one time. This can quickly lead to a cluttered console. This clutter can also serve to help the operator. Often humans spread paper over their desks to serve as a physical representation of what is going on in their heads [5]. For example, this personal organization can remind themselves of system issues they have to address or upcoming procedures they must monitor.

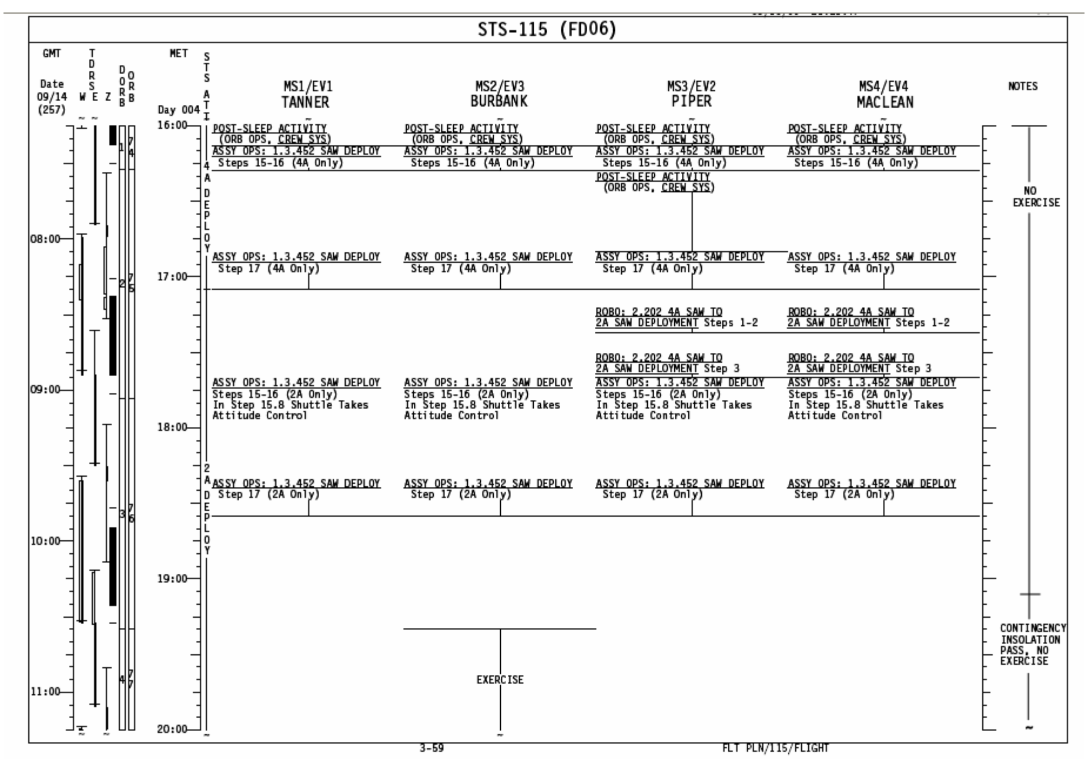

Figure 3. Shuttle flight plan page example from STS-115. [11]

Throughout each mission, GNC Support and GNC each maintain a flight documentation binder which includes handwritten shift logs, copies of shift handover reports documenting a summary of the shift's activities and present system status, hard copy of telemetry from specific points in the mission and documentation of mission events. These binders are used by the oncoming teams to get caught up with activities since their last shift and are maintained by the group as a reference document for that mission's activities.

Another important artifact near the GNC console is the refrigerator, microwave and vending machines. Most flight controllers have shifts averaging between 8 and 10 hours with only 5-10 minute breaks every few hours. Thus, having available food is important not only to keep controllers awake but sustain them through long shifts.

The console workstation serves as one way GNC support and GNC can exchange information. Since the WMPSR is located right outside the door of the WFCR, these two operators often share information face to face as well. The flow of information internal to the GNC discipline and with outside parties is depicted in the flow model shown in Figure 4.

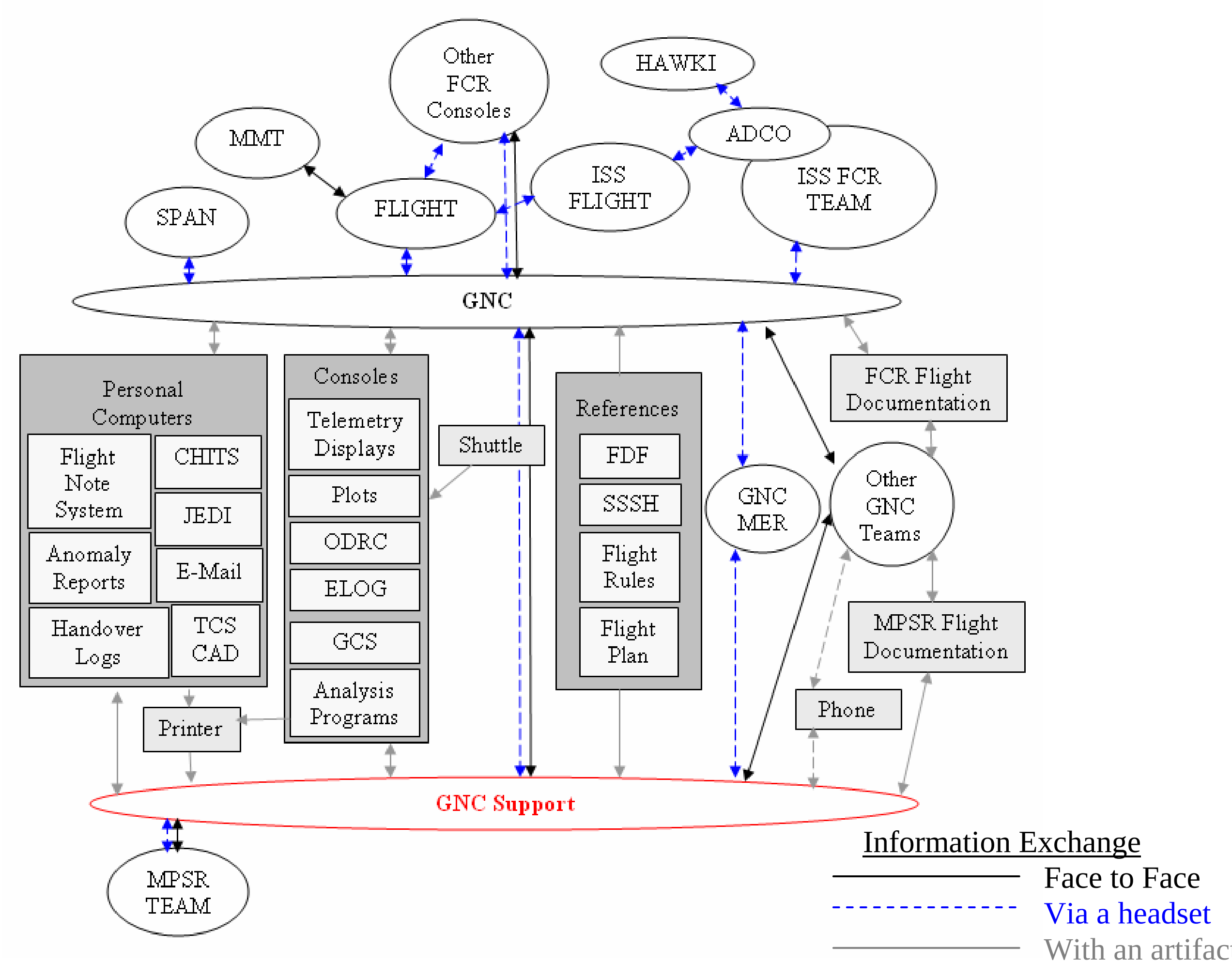

Figure 4. Flow Model for GNC Support.

During the orbit phase of flight, the GNC console operators primarily interface with the Flight Director ("FLIGHT"), the propulsion operator ("PROP") and the data processing systems ("DPS"). PROP is responsible for the onboard engines and jets. Their corresponding MPSR positions are "OREO" (OMS/RCS Engineering Officer) and "Consumables" which manages the onboard propellant. DPS is responsible for the onboard computers, the shuttle operating system and the serial data bus network. DPS has one MPSR position called "DPS Support".

GNC interfaces with several MER positions but most often with MER NAVAIDS (responsible for navigation hardware), MER GNC (responsible for DAP analysis), MER IMU, and MER Flight Control.

Similar to their FCR counterparts, GNC Support also directly exchange information with other MPSR team members, the GNC MER, on-coming and off-going GNC shift teams. While the flow model readily depicts the FCR operator's responsibility for the majority of integration, MPSR operators also exchange information of system status to assist with integration, and troubleshoot problems. For example, if GNC Support sees one of their systems has power failed, they will check with Electrical Power Systems (EPS) Support to see if they noticed a short on the corresponding electrical bus.

In order to effectively support their FCR operator, MPSR operators must be aware and monitor communication of their FCR with other consoles. This decreases the need to repeat information and increases situational awareness. MCC operates in a "chain of command" from the MPSR, to the FCR console to the Flight Director and out the SSP program Mission Management Team (MMT). Thus, clear communication is imperative since there are often several degrees of separation between the start and end of a communication line. Adding to the difficulty, most communication occurs via the DVIS system eliminating the benefits of face-to-face communication. The SPAN console position is usually staffed by a manager (often a former flight controller) who is responsible for integrating communication between the flight control team and the MER and managing AR documentations. This position helps insure flight events are properly documented for future reference and that necessary members of the SSP community are aware of events as required.

Notice on the flow model that GNC only receives information from the Shuttle and does not have the ability to send information to the vehicle. When GNC operators build a command on their workstations, the GNC FCR operator requests uplink permission from FLIGHT and then the Instrumentation and Communications Officer (INCO) performs the actual uplink of the command. The GNC console only uplinks a handful of commands to the vehicle during a typical fourteen day mission. Most system actions are dependent upon the crew flipping switches or entering commands into the shuttle computers.

The flow model depicts the large number of groups with which operators must coordinate activities. The large number of players inside of MCC also complicates communication by making sure all parties necessary are aware of information and knowing who to contact. The most difficult aspect of obtaining certification as a flight controller is communication. It takes hundreds of hours of practice to master monitoring loops, knowing when and to whom to relation information and how specific the information to be. Garret and Caldwell of Perdue University conducted a contextual inquiry of the ISS Gemini operators and found that management of information flow with MCC was critical due to the physically distributed nature of operators within the complex [6]. Mastery of information flow paths is important to ensure effective use of resources and that no controller makes a final decision independent of the rest of the time.

Garret and Galdwell identified four types of information that are exchanged in MCC [6]:

1. *Software* - internal to a single cpu on either ground or the vehicle exchanged through the workstation computers
2. *Command* – antenna configuration / availability and command uplinks sent from MCC to the vehicle

3. *Network* – data and telemetry streams between vehicle and computers on the ground as well as between each of the computers on the ground
4. *Knowledge* - voice loops over DVIS (managed by FD) (main instrument for knowledge sharing between spatially distributed controllers / astronauts)

Of the information types, Garret and Galdwell identified knowledge as the most difficult to maintain cognizance of, again indicating the communication challenges inside MCC.

The large number of groups in MCC makes it impractical for operators to have their consoles in the same room as everyone they integrate with, however as stated, physically separating operators is a challenge for communication. Figure 5 provides a physical representation of the layout of MCC.

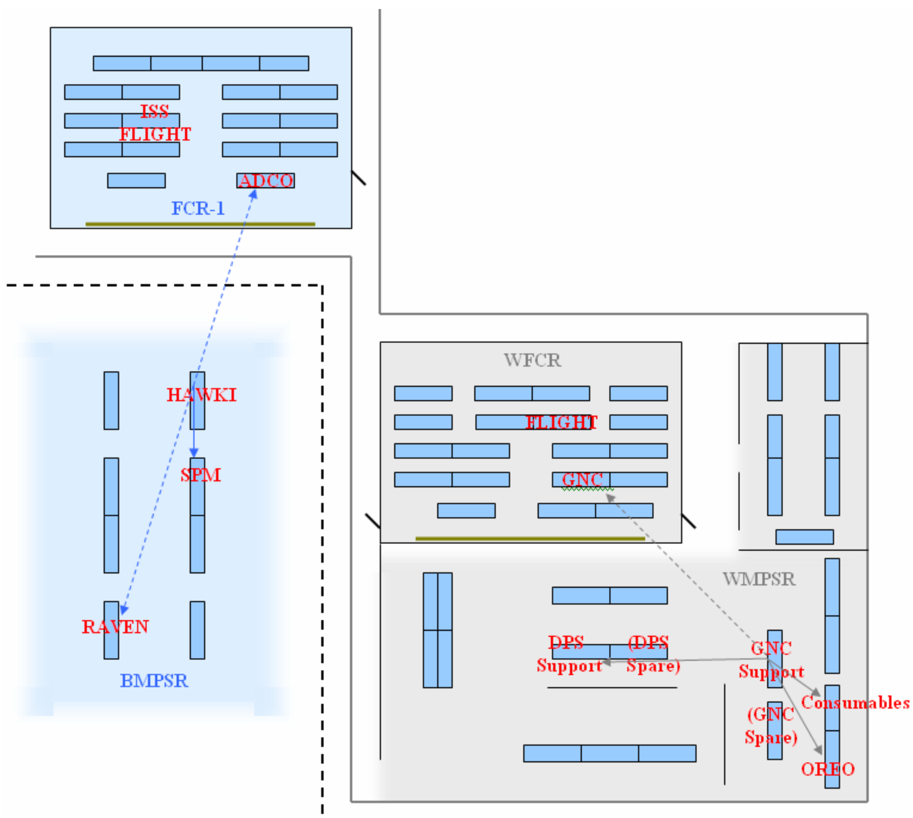

Figure 5. Physical Model of MCC (not to scale).

Arrows depict the most frequent consoles with which GNC Support exchanges information. Dotted lines depict communication which is difficult to achieve face-to-face due to physical separation. The physical model shows that the WFCR and WMPSR are located adjacent to each other which allows for limited face-to-face communication between GNC and GNC Support. The BMPSR, however, is located on a separate floor from FCR-1. Note that both the SSP and ISS MERs are on completely different floors from the other rooms. In order to allow operators direct communication with another, MCC relies on the DVIS system.

Due to the large spatial separation between operators, the physical model does not provide a good overview of console interaction. A model of the DVIS system is more informative (Figure 6). Watts, Woods, Corban and Patterson of Ohio State University conducted an ethnographic study to determine how the DVIS voice loops act as cooperative aids in MCC [7]. As a result of their research, they developed the following model of the voice loop structure from the perspective of a FCR operator. The model depicts the Flight Director's coordination with the FCR team on the "Flight Loop," that the CAPCOM only can talk on the Air/Ground loop to the crew, the FCR operators communicate with their MPSR counterparts via "Support Loops" and an example of the conference loops organized by discipline in the FCR (called "MOCR" loops). For example, GNC and PROP share a common FCR conference loop. There is also a conference loop for MPSR positions to coordinate with each other and a loop for each discipline to coordinate with their MER counterparts (These loops are not depicted in the model).

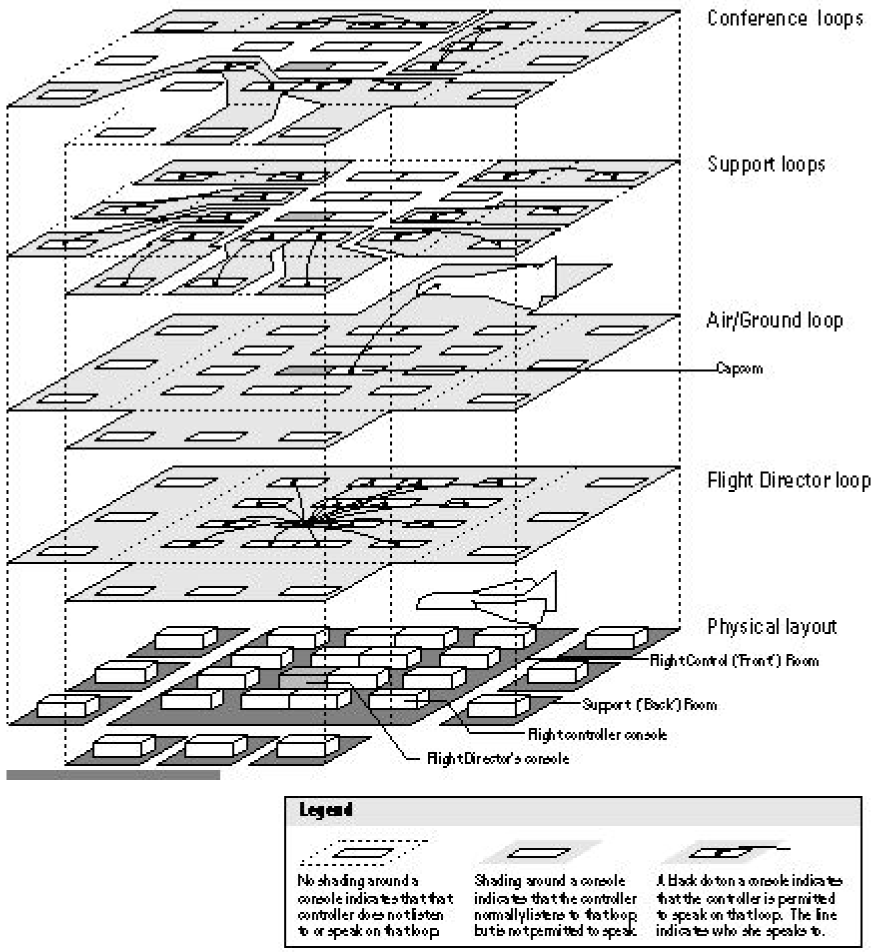

Figure 6. Model of voice loop structure for the SSP FCR and MPSR. [7]

The structure of the voice loops parallels the chain of command structure of MCC. The multiple loop system enables simultaneous conversations among flight controllers, however, this means that flight controllers must be able to monitor parallel conversations – a difficult task developed during training. To facilitate loop communication, MCC has adopted a loop protocol. To call an operator, a flight controller first states the name of the position they wish to call, their name and the loop they are on. Usually the calling operator will wait for a "go ahead" call from the position they are establishing communication with. For example, ADCO wanting to talk to GNC would say "GNC, ADCO on your MOCR." It is implied any call to FLIGHT is on the Flight Loop, so that loop is not stated.

All flight controllers from a discipline constantly monitor at least the air to ground loops, the flight loops of both ISS and SSP when in dual operations, their conference loop and their support loop. However, most controllers will monitor the conference loops which indirectly affect their system. For example, GNC monitors "MOCR DYN" which is the conference loop for Rendezvous and the Flight Dynamics Officer (FDO, pronounced "fido") during rendezvous.

The ability to monitor several loops at once is an important strategy for ensuring flight controllers have situational awareness of activities over the entire vehicle. The ability to listen to discussions on the loops allows controllers to pick up relevant events and activities without disrupting their ongoing work within the scope of their responsibility. Dourish and Bellotti [8] refer to this function as a passive awareness mechanism and Woods [9] calls it preattentive reference. By monitoring other loops, flight controllers can dynamically and opportunistically change their attention and activities with response to the change state of the shuttle systems [7].

Monitoring loops enable controllers to anticipate problems in their own system and be prepared for future actions especially since shuttle systems are interconnected. "Anticipation has also been found to be important in control rooms of other domains in which teams coordinate to handle high-tempo, uncertain situations" [5]. Anticipation is important because it allows controllers to synchronize their communication and actions over time. For example, if a failure occurs in a subsystem, the flight director will ask related subsystem controllers about the impacts of that failure on their systems. When controllers hear about the failure on the flight director's loop, they can anticipate questions from the director, and prepare to answer them without delay [7]. No mission is routine. Depending on the mission, about 30 to 90% of the mission activities need to be replanned while the mission is being conducted [10].

To aid a flight controller's ability to monitor loops, loops that are "enabled" to talk on have increased volume. Controllers can also program their DVIS panels to monitor specific loops at "high monitor" which increases the loop's volume even when the loop is not talk enabled. This volume capability, however, is very limited especially since loop volume is directly affected by the volume at which the speaker talks.

Figure 7 shows a sequence model depicting the typical actions taken by a GNC Support operator to resolve a problem onboard shuttle. A sequence model captures the most basic information about work practices including the intents of participants [3]. In the example of Figure 6, the trigger is a failure which occurs on board which is then noticed by the flight controllers. However, the trigger could also be the crew calling down to inform MCC of an abnormality. Steps in red have direct participation by GNC Support. The lightning bolts indicate steps which have the potential for "breakdowns" between them [3]. Due to orbital geometry, Shuttle does not always have a good line of sight to a TDRS communication satellite causing period loss of signal (LOS) which is a drop out of communication and/or telemetry. If a problem occurs during LOS, MCC will not be aware of it until acquisition of signal (AOS). If the problem does not require immediate attention and the crew is not available, then time has to be scheduled for the activity to be performed. Troubleshooting/resolution activities are often schedule for the end of the crew day but sometimes can be scheduled for many days in the future depending upon the criticality of the failure. The other possible delay can occur if the resolution requires a command and MCC is in LOS. The command cannot be uplinked until AOS.

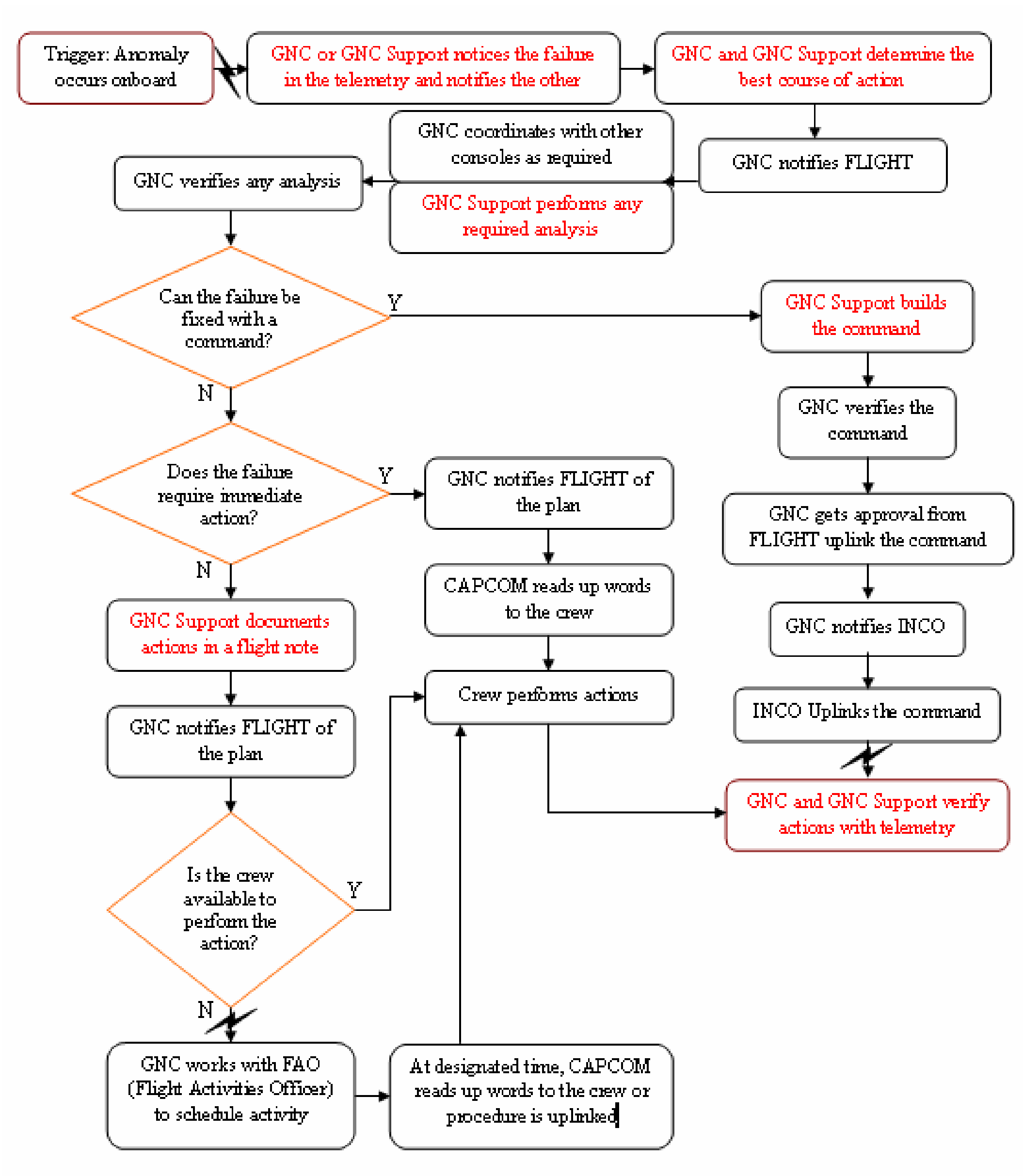

Figure 7. GNC Sequence model for resolution of onboard problems.

The above sequence model shows that GNC cannot uplink their own commands. For the shuttle, flight controllers build the commands on their workstations but INCO performs the actual uplink. The shuttle has very limited command capability so the vast majority of problems require the crew to physically type in item entries to the computer or throw switches. Thus with the Shuttle, the crew is prime for all troubleshooting and system reconfiguration activities.

HAwKI

Operation of ISS is fundamentally different to previous NASA missions. The space station never comes back to KSC for repairs and for the first time, MCC must closely coordinate with IPs including Russia, Europe, Japan and Canada – all who have their own control centers [10]. If human space operations is not hard enough, ISS control teams also must deal with the following complications:

- Multi-lingual communication
- Cultural and tradition differences
- Operations in different time zones
- International operators who are viewing different data due to the use different computer models and procedures
- Training while operations are ongoing
- A vehicle that is still being constructed
- Limited up-mass capability

Despite the many additional challenges, many aspects of operations at NASA's ISS MCC (MCC Houston, "MCC-H") are very similar to that for the Space Shuttle.

ADCO and HAwKI are responsible for the Space Station's attitude, momentum management for the four control moment gyros (CMGs) which provide attitude control, GPS, rate gyro sensors (RGAs). In addition to GNC hardware in the US Segment, ADCO also monitors telemetry from the Russian GNC hardware including star trackers, horizon sensors, GPS, thrusters, sun sensors, and magnetometers.

An artifact model depicting a physical representation of the HAwKI support console is shown in Figure 8. HAwKI's console is physically and operationally similar to that of GNC Support and the other MPSR positions. The differences are summarized below.

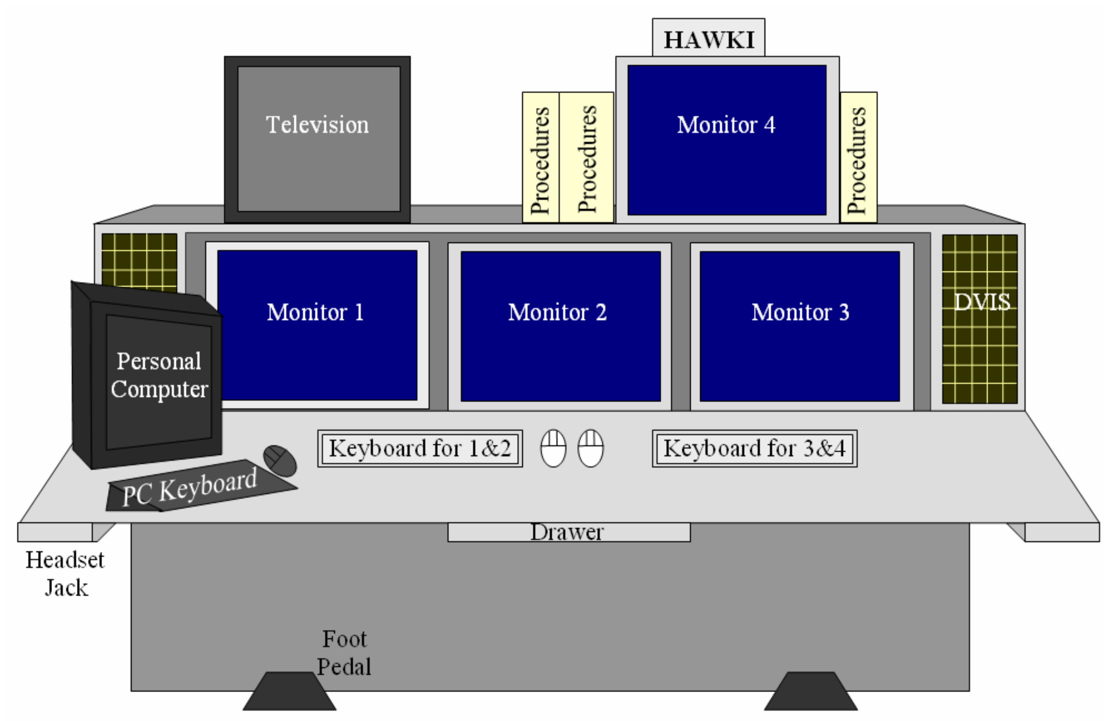

Figure 8. Artifact Model for the HAwKI console.

Monitor 2 is used for HAwKI's main displays called GNC Overview and Motion Control Group (MCG) Summary shown in Figures 9 and 10 respectively.

GNC Overview is structured very similarly to GNC Orbit. The font is noticeably smaller in order to put more information on the display. The display's structure strategy is also the same as GNC Orbit where the display is grouped by sub-system. Each blue box will bring up another display with more detail again the same as GNC Orbit. It is not surprising this display is so similar to shuttle displays because most of the original Station flight controller came from the Shuttle program.

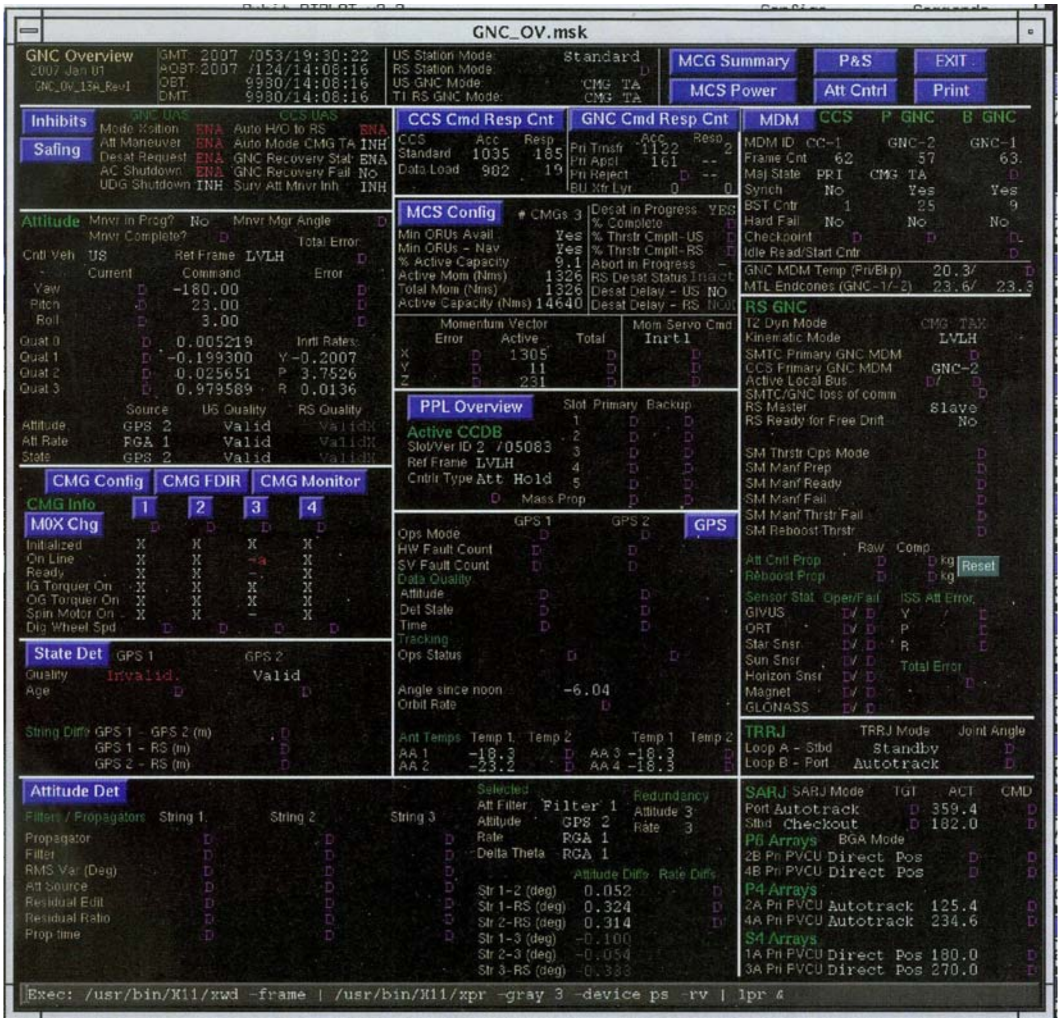

Figure 9. ADCO/HAwKI's GNC Overview display from a simulation.

The GNC Overview display also includes information about the location of Station's arrays. Since the array structure is very fragile, HAwKI must be aware of their orientation to know which modes of attitude control are allowed. For example, the Shuttle is not allowed to fire its large attitude control thrusters while docked unless the arrays are locked in a protected orientation. It is ADCO's responsibility to ensure the station is a good configuration for Shuttle attitude control. When ISS is ready, ADCO would notify GNC that the Shuttle can take over attitude control.

This display also has information about the Russian (RS) Segment generated state vector. The US and RS segments both generate their own attitude state and the ISS can use either at a time. HAwKI must keep monitor two separate GNC systems and states.

The MCG Summary display employs a very different strategy. The MCG display is intended to be viewed by the crew with their onboard laptops. Each system has a crew display to enable them view any telemetry and perform the same capabilities as the ground should it be required.

MCG Summary is very visual to quickly provide the crew and flight controllers high-level system awareness. Each piece of hardware is represented by a box. If it is currently being used to determine the attitude state, the box is blue. If the box has green corners, then the unit is powered ON. MCG Summary also provides a clear visual representation of the percentage of available CMG control torque momentum (control authority) currently being used to hold attitude. When the momentum exceeds 99%, the CMGs saturate and a loss of control (LOC) occurs.

Due to the ease of this display, GNC Support also uses MCG Summary for situational awareness when the Shuttle is docked to ISS.

Clicking on any hardware box will bring up another display with detailed information about that unit. The boxes at the bottom of the MCG Summary display bring up additional displays which provide the capability to send commands to the vehicle. Many of these displays are organized by the current activity and the display follows a procedure from top to bottom. An example of such a display used for docking is shown in Figure 11.

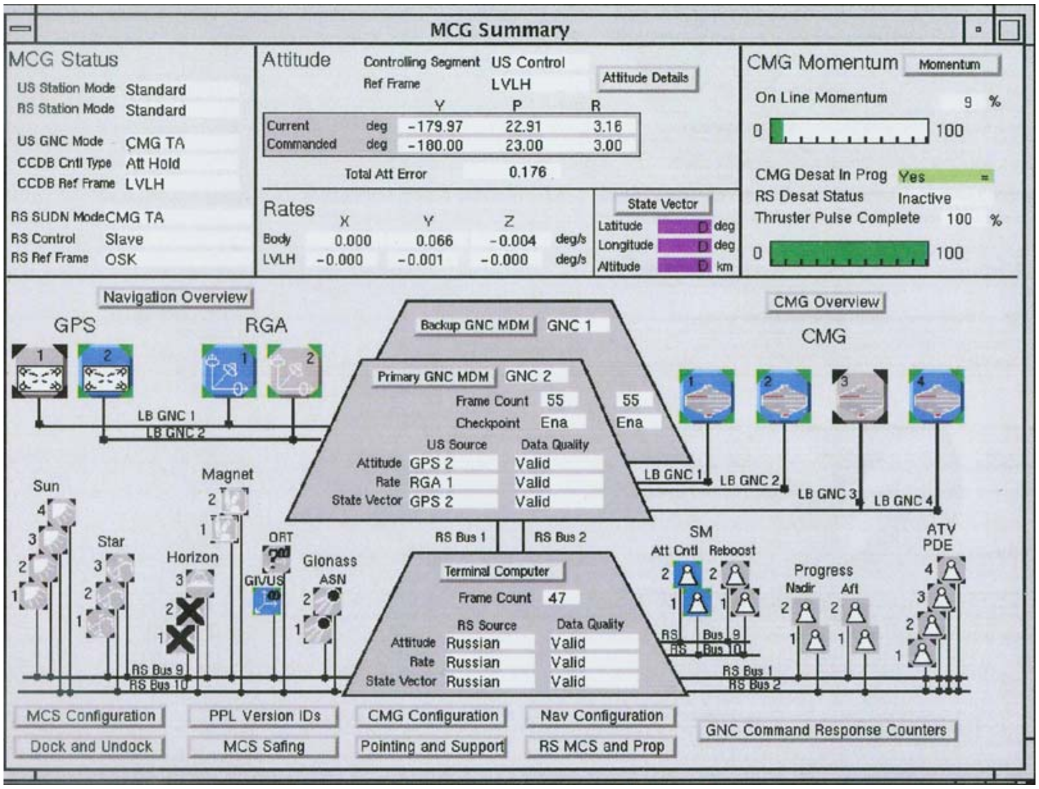

Figure 10. ADCO/HAwKI's MCG Summary display from a simulation.

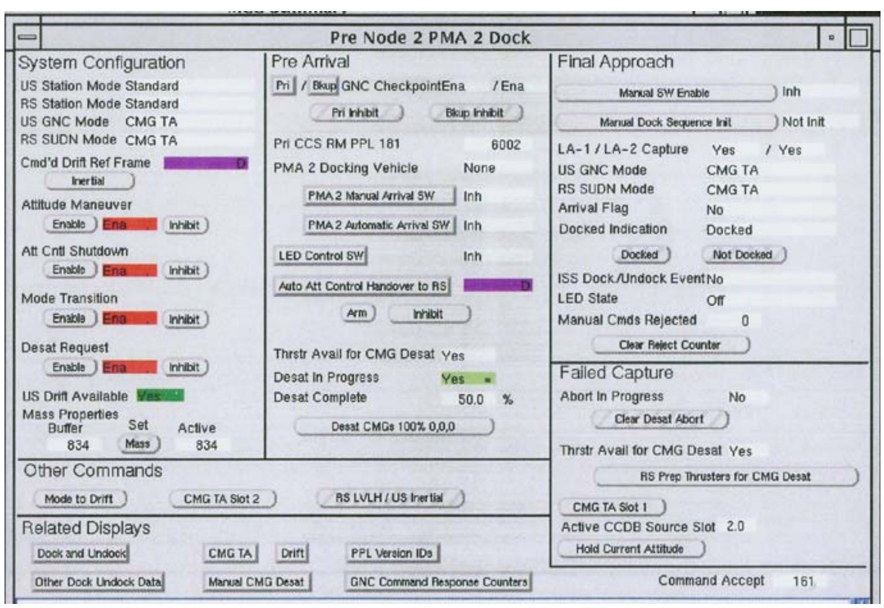

Figure 11. Docking command display example from a simulation.

The vast majority of steps in nominal procedures are performed via ground uplinked commands as opposed to the crew throwing switches on Shuttle. Thus as the Shuttle is docking to ISS (for example) HAwKI can monitor all required telemetry from the display in Figure 11. Commands to the vehicle are sent by click on the oval buttons on this display. HAwKI can follow along in the procedure and send the command right in order as they move from top to bottom on the display.

This display concept is very different than Shuttle. Instead of looking for indications on 4+ displays during docking as done by GNC, HAwKI (and the crew) have all the required information on one display. Thus, telemetry parameters are duplicated on several different displays. Organization displays in this manner increases the operator's situational awareness to the parameters that are important at that point. The operator can bring up the specific procedure for the current mission activity and immediate see all important information instead of filtering the items from general displays as done on Shuttle. The method of organization also can serve as a memory aid for the operator because everything they need to verify is right in front of them on one display. Finally, for a given task, the operator can document all the relevant telemetry with one display hardcopy. This also can provide a quick snap shot of relevant parameters with at the same time instance. Not every procedure has its own display such as Figure 11 – only the commonly performed and complicated procedures.

Each command must be built and stored on the server before the corresponding command button will work. Before each Shuttle flight, ADCO builds all the required commands as a group to limit the amount of work required during real-time operation. This allows the operators to take their time and eliminate errors which could occur when rushed during real-time operations. HAwKI will build any off-nominal commands that become necessary in real-time.

Unlike Shuttle, each discipline has the ability to send commands to the vehicle and ground commanding is the prime way to perform nominal and off-nominal procedures. This allows the crew to be free to perform science and hands-on maintenance activities. As a result, the ISS flight control team sends orders of magnitude more commands than Shuttle during a given time period.

HAwKI's monitors 3 and 4 are used for RT plots of current CMG total momentum used, commanded control torque, attitude errors, GMG gimbal angles, motors and the US Segment GNC rate errors. HAwKI's uses Monitor 1 to build commands and thus, the monitor has a command history tracker and a command sentry window that displays "GOOD" or "BAD" depending upon if the ISS has good command uplink. The command sentry box is rather large (about an inch square) to help ensure the operator does not try to command the vehicle during periods of ratty communication. Monitor 1 also has an events logger similar to ELOG and a Caution and Warning program similar to OFS. HAwKI used the television in the same manner as GNC Support. HAwKI does not have a display similar to GNC's CRANS.

The personal computer is much more important for an ISS flight controller than for Shuttle. In addition of the PC applications used by GNC Support, ISS flight controllers also view the majority of their procedures on the PC with an application called International Procedures Viewer (IPV) shown in Figure 12. Since HAwKI relies on electronic copies of their procedures, they do not have the need for the GNC Support's procedure stand. While HAwKI does have backup hardcopies of their procedures, the electronic copies are the prime resource. Since the procedures are electronic, the ISS team can be assured they always have the most recent procedure version as oppose to the manual paper updates frequently performed by SSP flight controllers. Electronic procedures also enable easy updates to procedures onboard ISS via uplink instead of relying on paper copies which would have to wait for a launch vehicle to bring them to Station.

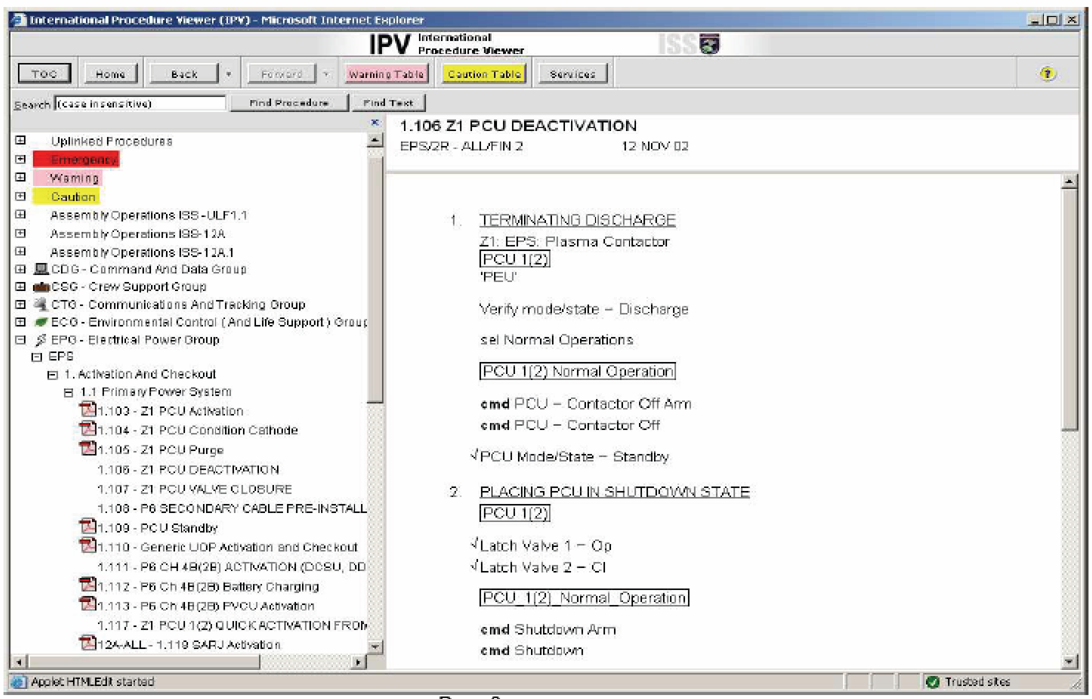

Figure 12. Screen shot of IPV [12].

Station procedures called Systems Operations Data File (SODF) are organized into about 30 books primarily by sub-system. Procedure organization is simpler with ISS since it only has one phase of flight: orbit. Instead of being organized by flight phase, many station procedure books are referenced by system. For example, there is a book for assembly operations, EVA instructions, robotic operations, and MCG procedures. ISS procedures are complicated, however, by the fact ISS is still being constructed. The addition of hardware to the vehicle can make entire books of procedure invalid. Thus, many ISS procedures and flight rules have “expiration dates”. Station controllers also have reference books available including the International Space Station Systems Handbook (ISSSH) which is ISS’s version of the SSSH, SCPs, and flight rules.

Since HAwKI relies on electronic procedures, they cannot make notes in the columns or set out a procedure as memory aid. Thus, HAwKI operators tend to keep a handwritten set of quick notes with things to do, procedure deltas to make and other reminders.

ISS flight controllers and crew members also use a PC application called OSTPV (On-board Short Term Plan Viewer) which is an electronic version of a flight plan and contains the same basis information as the SSP flight plan. As the onboard crew completes tasks, they mark the task as completed in OSTPV. The crew can also leave notes for flight controllers in the program. The ground copy OSTPV is frequently synced with the onboard version allowing ISS controllers to see the progress of the crew and obtain crew notes without relying upon air-to-ground communication. The use of OSTPV makes the crew much more autonomous than on Shuttle. A screen shot example form OSTPV is shown in Figure 13 and can be compared with the SSP flight plan page example of Figure 3.

In keeping with the electronic theme of ISS MCC operations, ADCO and HAwKI also keep their console logs via the PC instead of handwriting them as with GNC. The electronic log automatically time stamps entries as the operator types. The electronic logs are also more efficient for historical documentation purposes than with GNC’s mounds of paper in binders.

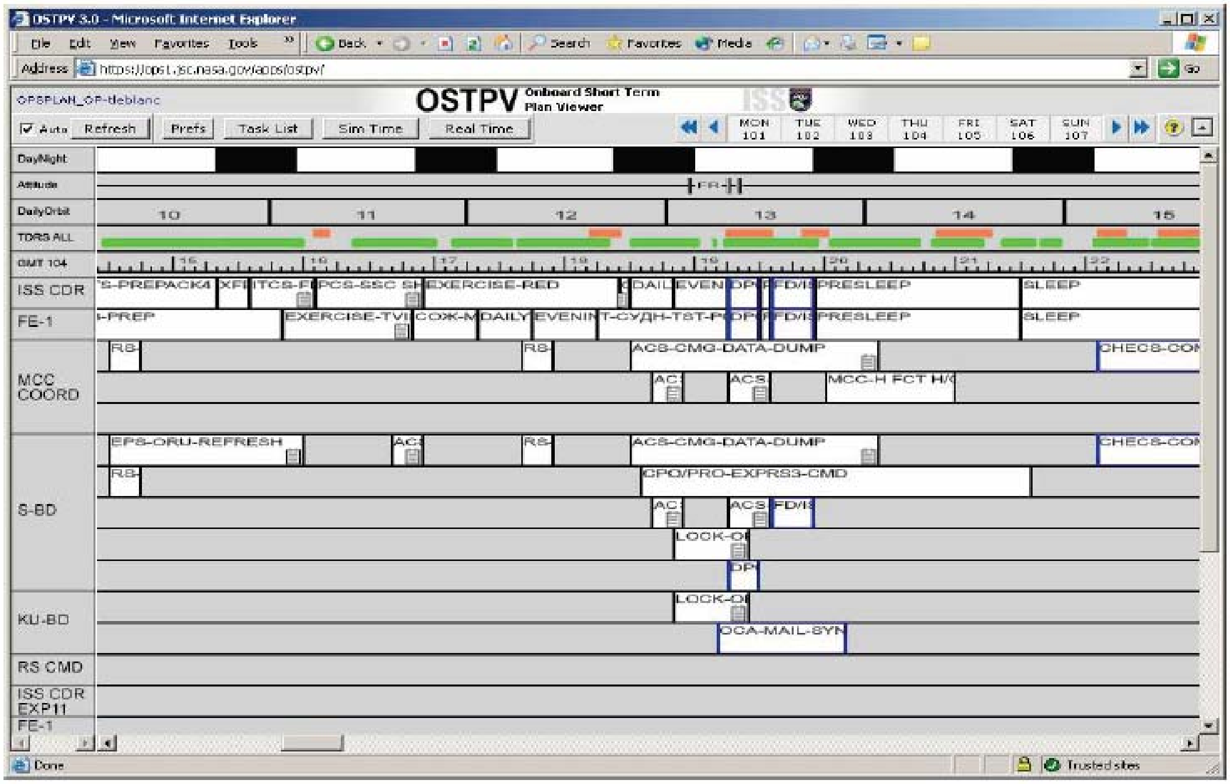

Figure 13. OSTPV screen shot [12].

As with the console operations, information flow within the ISS flight control team is similar to that of Shuttle's as shown in Figure 4. Since ADCO uses the PC to document flight activities, the computer becomes a key tool of information exchange between other shift teams. Also different on this Flow Model is the Russian Interface Officer (RIO) who coordinates between the US ISS MCC and that in Moscow. Similar to the SSP, ISS also has an MMT which is called the International Mission Management Team (IMMT). ISS program managers from all countries of participation serve on the IMMT.

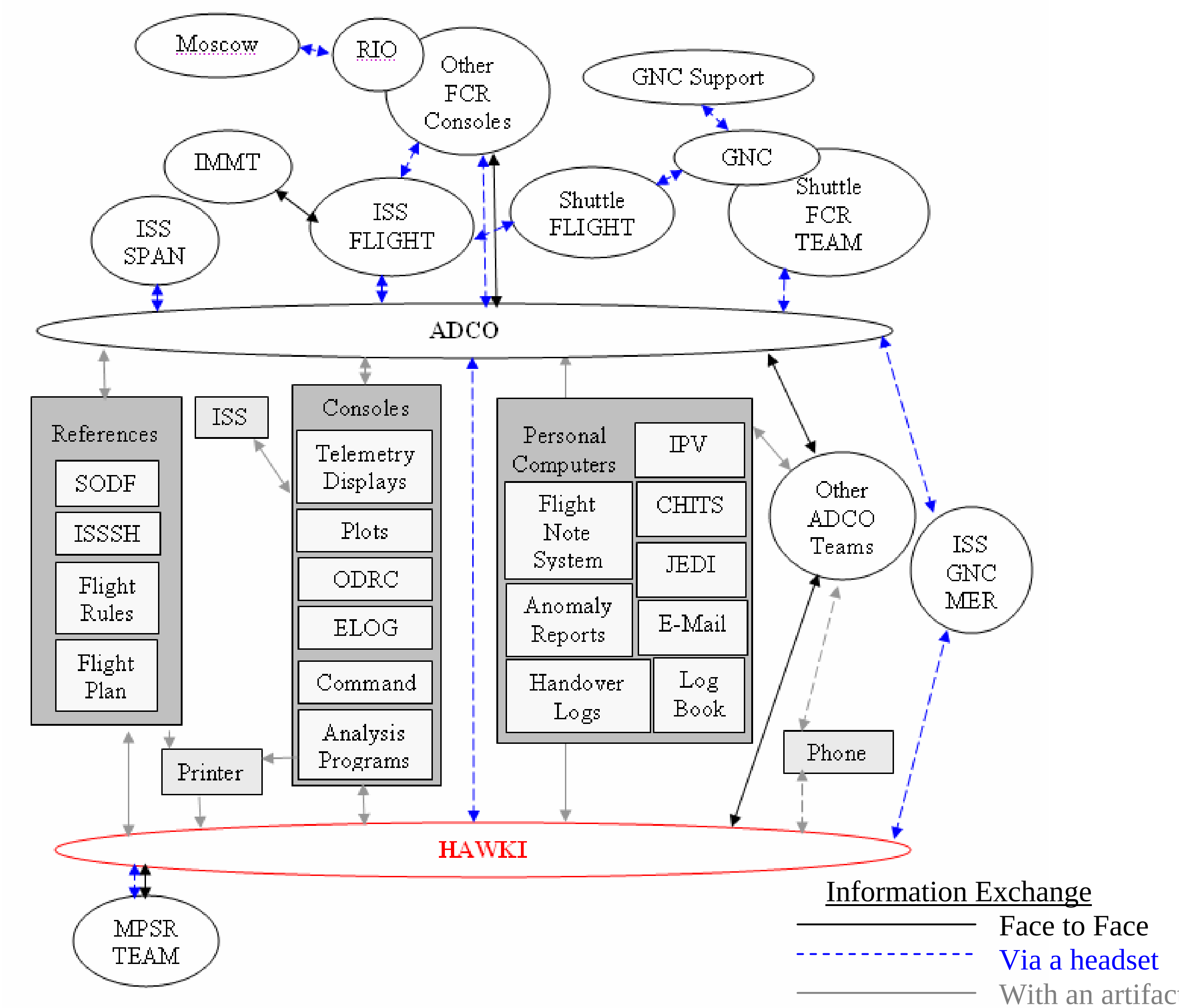

Figure 14. Flow Model for HAwKI.

From HAwKI's point of view, the biggest difference between HAwKI and GNC Support is that it is very difficult for HAwKI to talk face to face with ADCO. As evident in the physical model shown above, the BMPSR is on a different floor from FCR-1. During the simulation I observed, ADCO and HAwKI never talked face to face. GNC and GNC support, in contrast, talk face to face about every two hours for a few minutes. Thus, ADCO flight controllers do not have the face time as with GNC to more easily talk through anomalies.

Another difference with this flow model is that the arrow from the console to ISS is two way since HAwKI has the ability to directly command the vehicle. Since there are multiple consoles performing frequent commanding to the vehicle, all commands are coordinated on the DIVS loop "FMT Coord" which is monitored by all operators sending commands. When HAwKI is ready to send a command, they enable their position to command and click on the corresponding oval button. This brings up a pop-up window that says the command is unsafed and enabled. ADCO confirms the command is ready to HAwKI. HAwKI then checks goes to FMT Coord to ensure no other operators are sending a command and announces, "HAwKI sending command to *(command purpose)* on my mark, 3, 2, 1 mark." HAwKI then sends the command via a button on the workstation on the mark. ADCO and HAwKI confirm the command is accepted by ISS and verify it in the telemetry.

Adding to the difficulty of monitoring loops, many ISS loops periodically have Russian speaking with a translator. The bi-lingual nature of the loops, while minimized, adds to the loop clutter and increases the average volume level of the loops.

HAwKI most often interfaces with the MPSR operators Systems Resource Manager (SRM) who is responsible for the positioning of the solar arrays and with the Resource Avionics Engineer (RAVEN) who monitors the onboard data and computer network. HAwKI interfaces with RAVEN to uplink commands which change software parameters, such as mass properties. These types of commands can only be uplinked by RAVEN. The physical layout of HAwKI and these consoles are shown in the physical model of Figure 5.

The sequence model for resolution of onboard problems is shown in Figure 15.

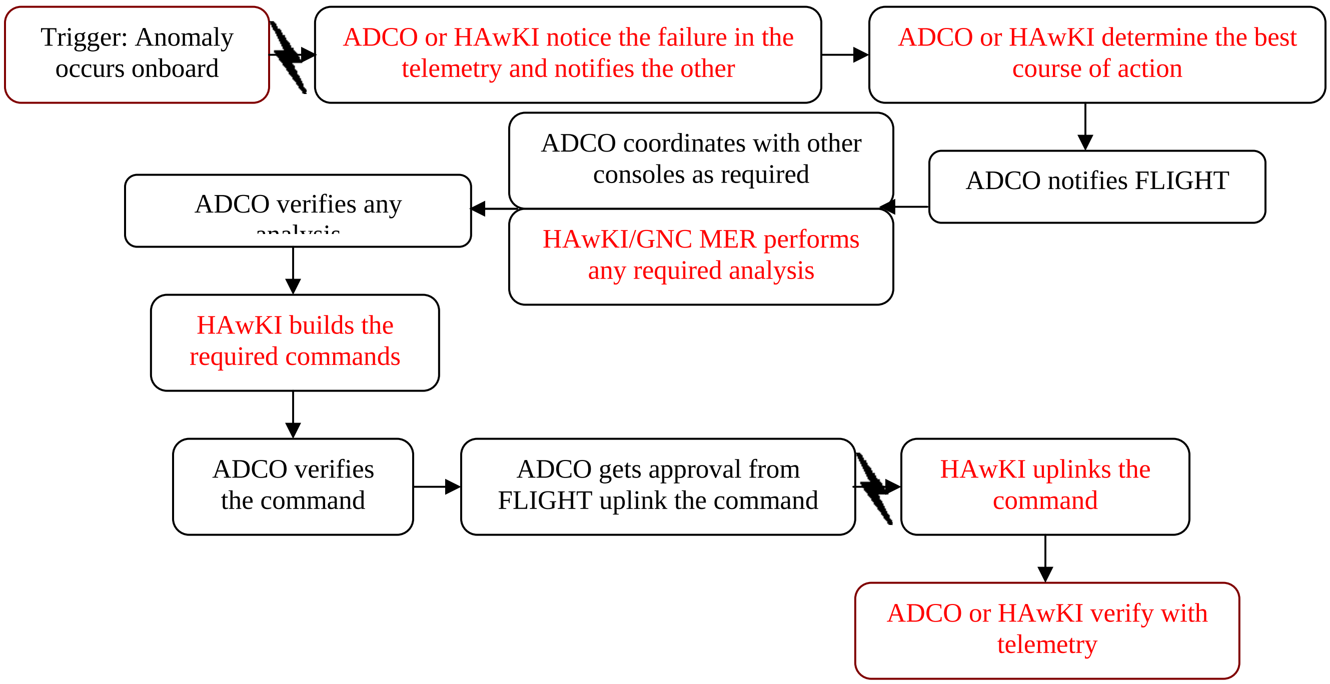

Figure 15. HAwKI Sequence model for resolution of onboard problems

Since ISS flight controllers are prime for problem resolution, the sequence model for resolving problems is simpler than compared to that for Shuttle. The same breakdowns, however, are apparent within the model for LOS.

A significant difference in the sequence for problem resolution, however, is the increased participation of the ISS MER. ADCO's ISS MER counterpart is called GNC. Unlike GNC Support who performs the majority of analysis for the console, ADCO's MER provides analysis support. For example, GNC Support will calculate any required IMU biases, IMU compensations, required OMS TVC trim loads, star line of sight vector uplinks, etc. GNC only contacts their MER when they have a question or if the internal parameters of the DAP need to be changed (this is a MER call). In contrast, ISS MER GNC calculates any required changes to CMGs, any attitude biases necessary, etc, and provides the analysis to ADCO/HAwKI which perform implementation.

References

[1] Dumoulin, Jim. *Lyndon B. Johnson Space Center*. Online. Available: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-jsc.html#sts-jsc-mcc. Feb. 12 2007.

[2] *Principles of Contextual Inquiry*.

[3] Beyer, Hugh and Karen Holtzblatt. *Contextual Design: Defining Customer-Centered Systems*. San Francisco: Morgan Kaufmann Publishers. 1998.

[4] Bainbridge, Lisanne. *Ironies of Automation*. Automatical. Vol 19, No. 6, pp.775-779. 1983

[5] *In praise of clutter*. The Economist: The Economist Newspaper and The Economist Group. Dec. 19, 2002.

[6] Garrett, Sandra K., Barrett S. Caldwell and Anthony Bruins. *Information Sharing and Knowledge Management in MCC System Evolution*. NASA/ASEE Summer Faculty Fellowship Program: Johnson Space Center. Contract Number: NGT 9-54. Aug. 3, 2007. Online. Available: http://grouper.ecn.purdue.edu/papers/private/SFFpaper-Final.doc, Feb. 16, 2007.

[7] Watts, Jennifer C., David D. Woods, et al. *Voice Loops as Cooperative aids in Space Shuttle Mission Control*. Boston: ACM Conference on Computer Supported Cooperative Work proceedings: 1996. Online. Available: http://interruptions.net/literature/Watts-CSCW96-p48-watts.pdf. Feb. 12, 2007.

[8] Dourish, P., & Bellotti, V. *Awareness and coordination in shared workspaces*. In Proceedings of the CSCW'92 Computer supported Cooperative Work. Toronto, Canada. 1992. Online. Available: http://projects.ischool.washington.edu/mcdonald/courses/info447_wi05/wk5/Dourish.Awareness.CSCW92.pdf. Feb. 12, 2007.

[9] Woods, D. D. *Cognitive Demands and Activities in Dynamic Fault Management, Abduction and Disturbance Management, in N. Stanton (ed.), Human Factors of Alarm Design*. New York: Taylor & Francis. 1994.

[10] O'Neill, John and Roxana Wales. *CSCA Issues Raised by Mission Control for the International Space Station.* NASA Ames Research Center. Moffett Field, CA. Online. Avalable: http://d3e.open.ac.uk/cscl99/ONeill/ONeill-paper.html

[11] STS-115 FD6 Execute Package. Sept. 14, 2006. Online. Available: http://images.spaceref.com/news/2006/157660main_fd06_ex_pkg.pdf. Feb. 27, 2007.

[12] Leblanc, Troy P. *Mission Control Center Web System*. AIAA Workshop on Enhancing Space Operations. May 4, 2005. Online. Available: http://www.aiaa.org/tc/sos/ws2005/docs/3Tools%20&%20Tech/MCCWebAIAA.pdf. Feb. 27, 2007.