LESSONS LEARNED IN CONCURRENT MISSION AND SYSTEMS DESIGN AT NASA GLENN RESEARCH CENTER: ALMOST FIFTEEN YEARS OF THE COMPASS TEAM

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ABSTRACT

This paper is a retrospective of the lessons learned during the almost 15-year history of the Compass concurrent mission and systems design team at NASA's Glenn Research Center (GRC). It examines the key factors in the team's evolution from a temporary group gathered to perform a single study to the successful, sustainable team it is today. Compass is a matrixed team of experts with various technical backgrounds and personalities. They collaborate over a two-week period either physically in a dedicated meeting space, or virtually to design a space system (Spacecraft, stage, science package, etc). Over the years, because of the rapid nature of the design studies, the team leadership has iterated on the optimal team member personality makeup, facility elements and tools as well as NASA GRC management support necessary to lead to sustained success.

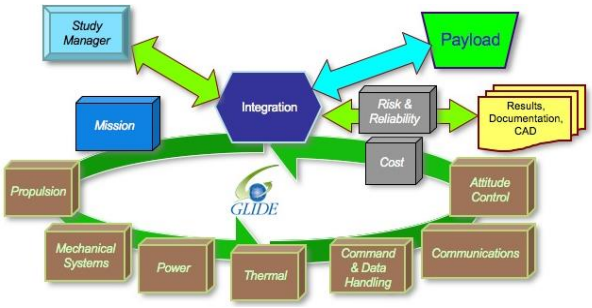

Figure 1. Notional Compass Design Session Process

1. INTRODUCTION

Established at NASA's John H. Glenn Research Center (GRC) in 2006 to meet the need for rapid mission analysis and multi-disciplinary systems design for in-space and human missions, the Compass Team is a multidisciplinary, concurrent engineering group whose primary purpose is to perform integrated systems analysis for space-based missions quickly and cheaply. The team was established to assess spacecraft and space systems concepts and represents a logical extension of GRC's long history of design and analyses of space systems concepts and missions.[1]

Figure 2. Compass Logo

2. TEAM ORIGIN

With a focus on the applications of NASA's advanced technologies, the Compass Team is capable of designing any system that involves one or more of the disciplines present in the team. The authors have been involved in both the initial development of the Compass Team and its design process, as well throughout its fifteen-year existence. The team draws some of its current collaboration process and tools from work done in the early 2000s as part of a collaborative effort between NASA GRC in Cleveland and the Jet Propulsion Laboratory (JPL) in California in support of the multi-center Jupiter Icy Moons Orbiter (JIMO) spacecraft design. NASA launched the Compass Team in 2006 as part of its lunar landing studies during the Constellation Program. After this initial design, the team found an ongoing purpose and identity focused on designing reference missions for the application of technologies that drive NASA agency technology development programs.

3. CUSTOMER FOCUSED

The Compass Team has found great success by being wholly customer-focused. This is essential throughout the design study process. The customer is responsible for determining the design goal, funding the study, participating and providing guidance/goals throughout the process, and helping to define which products will eventually be of the greatest value. Although the Compass Team shapes the design, lends expertise, gathers the findings, and creates comprehensive chart packages and reports, ultimately the customer takes ownership of the Compass products and decides how to use those results.

The Compass Team lead believes that no design team can exist long-term without direct customer funding. A

"standing army" organization may not have the same requirement to create consistent, high-quality products, because they are not directly sponsored by their customer. Direct customer funding motivates the team to higher performance levels, thus encouraging return customers and providing the ability to leverage current customers to find new customers. This customer focus has led to a consistent base of customers who value Compass products, invested in and aid the process, and are willing to encourage other customers to engage with the team. The primary lesson here is that a team must create the highest quality products in order to continue to cultivate return customers.

An additional benefit to being customer driven and customer funded is that the customers (representatives from programs and projects across NASA, academia, and industry) do extensive upfront work to select the design they want to fund. It is inefficient to work on a poorly defined project; therefore, the Compass Team is engaged for customer-selected "biggest bang for the buck" studies. This removes the burden of developing design ideas, establishing the ground rules and goals, and then trying to find a customer to buy the resulting product. Instead, the Compass Team tailors the design specifically to the customer's needs.

The Compass Team encourages the customer to sit in and participate in the design sessions. Since the customer is the ultimate decision maker, this saves valuable time. As the team explores options in a design, the customer is able to listen and be aware of the pros and cons of each choice. When the time comes to make a decision for the point design, they are prepared to do so without needing a separate briefing to recap what led the team to this decision point.

As the product owner, the customer is able to decide how best to use the products (e.g., publish them, use them as management decision-making tools, or put them forward in a proposal). Once leaving the Compass Team, designs have sometimes changed to best suit the customer's needs. An example of this is the design that would eventually enable what is now known as the Power and Propulsion Element (PPE). [2] Originally called Fetch by the Compass Team, this concept used a high-power Solar Electric Propulsion (SEP) stage to rendezvous with and capture an asteroid. The Fetch design was done in collaboration with the Keck Institute as part of their Asteroid Retrieval Feasibility Study.[3] This study gave birth to the NASA Asteroid Redirect Robotic Mission (ARRM).[4] When ARRM was cancelled in 2017, the SEP stage became the PPE. The PPE is the first element of NASA's Gateway Mission, which supports the Artemis Program to return to the moon.[5]

Finally, it is important to note here that, since the team is a small, customer-focused group, they are able to tailor any products to best suit the needs of the customer. It is more important to ensure the design and products meet the needs of the customer and answer the customer's questions, than to have a rigid "standard" product set.

4. PEOPLE

The Compass Team and process work entirely because of the team members. It is all about the people! Although many members have worked on the Compass Team, we have found that a number of specific traits help indicate which members are likely to stay long term.

4.1 Team makeup: Skills and Systems Thinking

The Compass Team is comprised of the team lead, systems engineer, mission designer, configuration lead, cost estimator, and subsystem leads. These subsystems include attitude determination and control (AD&C) (also sometimes referred to as guidance, navigation, and control [GN&C]), propulsion (including both chemical propulsion and electric propulsion), structures and mechanisms, thermal control, command and data handling, communications and tracking, electrical power systems (including both nuclear, and non-nuclear systems), and science. Depending on the particular needs of a study, additional expertise can be included or excluded. The team has also recently added a technical editor position, to aid in documentation and report writing.

Although each team member is responsible for leading the design of their particular subsystem, it is important in the Compass environment to cultivate a culture of systems thinking. This prevents one subsystem from making decisions for their part of the design without considering the impacts those decisions will have on other subsystems. It encourages the subsystem leads to work together to figure out which data needs to be shared between them to best capture their systems. Additionally, systems thinking encourages the whole team to engage in the problem solving process, as they not only recognize that each decision affects their system, but also that there is a benefit in exploring a problem from multiple angles. Although the systems engineer is there to assist in this process, the subsystem leads must be able to work together as well.

Communication skills are essential. Since the design is forming in real-time, members need to be able and willing to step into the conversation to voice ideas, concerns, or questions. It is important to cultivate an open and safe culture to enable open and honest communication.

Creativity is key as well. Customers approach the Compass Team with unique problems. The team members must be willing to think beyond standard solutions to find innovative approaches. If the answers were straightforward, the customer would not have

approached the team in the first place. However, creativity without grounding in reality creates risk. The team succeeds because it combines and balances the dreamers and the realists.

This combination of creative and grounded thinkers is both rewarding and challenging. The solutions the team devises are innovative, but this relies on the team lead's ability to balance those who want to make assumptions and jump to the end, with those who never want to narrow down the trade space and prefer to carry every option forward. Balancing exploration of the trade space with developing a fleshed-out point design is tricky and requires experience and practice.

The team lead has often described this design process and their role in it as being similar to the traveller from the European folk tale "Stone Soup." In this story, a traveller with no food sets up a pot filled with water and adds a single stone to make stone soup. As the children of the town are entranced, the traveller asks them to share other ingredients to enhance the stone soup, eventually making a large, delicious meal that can be shared by all. The traveller removes his stone at the end and presumably moves on to the next village. In the Compass design process, the team lead throws in the stone, the first ingredient, and then encourages each team member to contribute from their areas of expertise. As the design continues, the product becomes richer until the point design is complete. At that point, the team lead can take his "stone" on to the next design.

4.2 Team makeup: Personalities

The Compass Team has a saying that the team produces "80% of the answer in 10% of the time." This fast-paced environment is only possible if the team members can accept that they will never have the ability to answer 99% of the problem since this is such an early-phase, feasibility-centred team. In the team's experience, some team members thrive in this environment, because they want to explore interesting new problems, make and document carefully chosen assumptions, devise potential solutions, and move on to the next exciting problem. The team calls them the "80 percenters." However, the team has also found that members who prefer to dig into the details and find the "99% solution — "the "99 percenters" — are not happy on the team. They find it difficult to move on to a new problem before the first one is thoroughly solved, and eventually leave to join programs and projects that can make better use of their keen attention to detail.

The Compass Team lead has been using the Myers-Briggs Type Indicator (MBTI)[7] to examine how these preferences play into successful team dynamics. This ongoing work merits future discussion, but some top-level observations are noted here.

Introversion and Extraversion- Although the Compass Team, being an active, real-time team lends itself to extraverts, the team has found a large number of introverts flourish in this environment. Since the core team is only approximately twelve people, and the work is often discussed in smaller sub-groups, introverts feel comfortable sharing their ideas and expertise. In fact, the current team is made up of a majority of introverts. Another plus side of having both extraverts and introverts on the team is a tendency to address problems in different ways. While the extraverts thrive in the real-time problem-solving environment, the introverts are often the team members who catch mistakes or omissions between design sessions, when they have the time to look at the problem on their own.

Flexing- Myers-Briggs discusses preferences, which is not to say that individuals cannot operate in ways different from their preferences, just that it takes more energy to do so. The Compass environment tries to capitalize on each person's strengths and tries to ensure that no one is forced to operate outside their comfort zone for prolonged periods of time. Over time, more mature team members are often more comfortable flexing.

Finally, the team has found the greatest success when the team lead and systems engineer have complementary traits, rather than the same traits. One of them must be able to kick off new ideas (a "starter"), but the other must be able to run them through to a conclusion (a "closer"). This dynamic creates a robust leadership team and ensures that one of the two is free to move on to the next design, while the other wraps up communications with the previous customer.

4.3 Team makeup: Organization

The Compass Team is made up of members matrixed in from GRC's technical organizations. Other than the team lead and systems engineer, no team member works 100% of their time for Compass. This is an extremely beneficial set up because it means that the team members are actively working on other, real-world projects at the same time and are engaged with other members of their technical organizations. This keeps team members up-to-date on the latest developments in their fields, gives them a cadre of other technical experts to bounce ideas off, and provides a group that can peer review their work.

Since Compass addresses many different mission designs and ideas, another positive effect of a matrixed organization is that each team member brings a unique toolkit with them. There is no standard set of tools that subsystem leads are required to use, instead, they develop, augment, refine, and test their own tools with each new study. Over the past 14 years, this has led to ever-evolving toolsets that continue to improve the products. (Section 5. TOOLS discusses this subject further.)

Another benefit of utilizing individuals from other

organizations is that there are multiple people trained and prepared to step into a Compass design for a single subsystem. This means a single person going on vacation or getting sick does not halt team progress, another team member can be "pulled off the bench."

The matrixed organizations also reap positive benefits from this arrangement. The Compass environment provides the ultimate training ground for new hires. Often the more experienced team members will bring new employees from their areas of expertise with them to learn the ins and outs of designing a spacecraft. Since the studies are fast-paced and ever changing, the new hires are exposed to many types of missions in a relatively short period and learn how their subsystem connects to the others in a spacecraft. A side benefit of the addition of new hires is that the team is infused with new ideas and energy. When the team has the same membership for too long, without any new additions, the ideas can fall back into being routine, rather than inspiring.

5. TOOLS

In order to make an engineering design team successful, the next ingredient is the analysis tools. The right people using the right tools can make all the difference. The goal of the Compass Team is not to design the final flight prototype, but rather to find a feasible solution. Therefore, the analysis tools used are those that are able to perform simplified analyses.

5.1 Individual Subject Matter Expert Tools

The Compass Team is comprised of experts in their subsystem design, and each of them bring along tools in their specific discipline to perform the analyses needed to design their subsystem. Some of the tools are homegrown first principles modelling spreadsheets while others are high fidelity analytical optimization tools.

For example, the Mission Design seat rotates between the members of the NASA GRC Mission Design and Analysis Branch. These members choose from a variety of different trajectory tools such as NASA's high-fidelity tool, Copernicus, the more simplified General Mission Analysis Tool (GMAT) and the Evolutionary Mission Trajectory Generator (EMTG), or basic Hohmann transfers or delta V calculations done in a spreadsheet. The analysts know best how to solve the problems presented and what tools to bring to the solution space.

Another key tool used in every design session is the Computer Aided Design (CAD) tool Solidworks®. The Compass configuration seat uses Solidworks® to lay out the design as the session transpires, checking to make sure that all elements included in the master equipment list make their way into the CAD model. This model is used both for placement of items as well as to estimate packaging both internal to the spacecraft as well as inside the relevant launch vehicle. It is also used to provide data such as moments and center of gravity to the GN&C designers and surface area to the thermal system designers.

5.2 GLIDE

When the Compass Team was assembled, it was decided that having an error-free way to share data between the subsystem experts was key to enabling rapid design studies. Automating the transfer of data between members of the Compass Team reduced the potential of errors in sharing data through less automated means such as copy/paste from emails or text, or worse, via verbal discussions. Key to this automation was the development and application of the data sharing tool, GLobal Integrated Design Environment, GLIDE [6].

GLIDE is a client-server software application that was designed to mitigate issues associated with real time data sharing in concurrent engineering environments and to facilitate discipline-to-discipline interaction between multiple engineers and researchers. There are three parts to the GLIDE implementation.

Figure 3. GLIDE logo

Because most engineers have access to Microsoft® Excel®, the first part of the GLIDE triad took advantage of Excel® as the user interface. This Excel® add-in is installed on the end-user's system and a GLIDE enabled workbook tracks each design session. Once the add-in is installed, any Excel® workbook can become linked to the GLIDE database in order to push or pull data from the database. These hooks set up the Microsoft® Excel® spreadsheet to send and receive data between the team members in a design session. This add-in continues to be updated with each Microsoft® Excel® update in order to maintain functionality and relies on the visual basic macro language available in Excel®.

The second piece is the GLIDE client application that runs native on either Microsoft® Windows® or Apple's® Mac OS® personal computers. The Compass Team has long been a proponent of operating system diversity and supports the use of the right tool for the individual analyst. Written in different languages over time, the client is currently written in Python®. The client interfaces between the Excel® spreadsheet that has been linked via the GLIDE add-in and the third part of GLIDE, a backend database running on a server.

The GLIDE database sits on a server that is securely protected behind the NASA Glenn firewall, and is

accessible only to users that have been granted permissions. The GLIDE application, which resides on the user's computer, does all of the communications to/from the database server. Data is passed to the database in named value pairs, and ownership of data associated with a variable is assigned by the system on a first come, first served basis.

Management and setup of a container to hold the data for each design session is done via a web interface. This interface has gone through several different iterations over the years and currently uses the Ruby on Rails® web application framework. The lead system engineer sets up each individual study container in the database through this interface, capturing relevant data to document the study for future use or reporting.

5.3 Distance Collaboration

During the recent COVID-19 Pandemic, the Compass Team shifted to remote operations. Although the organic design nature that comes from sharing a room cannot be replicated in its entirety remotely, the team found success using a number of approaches.

All meetings are conducted using the Microsoft Teams® platform. This allows the team to share video, share screens, use the chat function, and share files all through the same application.

While conducting these virtual, real-time sessions, the team also found it helpful for as many people as possible to share video. The video helped compensate for the lack of non-verbal cues that the team relies on such as, seeing when someone wants to speak, helping to not cut someone off mid-sentence, or seeing when someone has stepped away from their computer.

The team has typically operated with 3.5-hour long design sessions without any official breaks. As people needed to leave the room, they did so. However, with the advent of virtual meetings, the team found it more difficult for folks to step away and found energy wearing out in 3.5-hour long meetings with no breaks. As a result, the meetings were modified to run 4 hours, with a 10-minute break on each hour. This had remarkable, positive effects on morale and productivity.

A downside of the remote environment has been the need to use the NASA virtual private network (VPN) during sessions. Since the team is no longer located physically behind NASA's firewall, it is necessary to "remote-in" through the VPN to make use of the GLIDE software. Unfortunately, the VPN has had deleterious effects on internet speeds, which can impact team members' ability to share clear video and audio. The addition of a dial-in number associated with the Teams meeting has helped members at least be part of the conversation, even when the internet is not at peak speeds.

6. FACILITIES

An important part of the Compass Team is the dedicated Lab space used during the design sessions. This includes everything from the room itself to the equipment. The area must encourage productive face-to-face interaction while simultaneously enabling electronic data exchange.

6.1 Room size and configuration

The main room of the Compass Lab features five identical custom tables. Each table can seat up to four subsystem leads and includes power and internet connections. The tables are outfitted with additional monitors to increase the screen real estate of the team members, allowing them to be more productive. The center table seats the team lead and the customers, as well as any other visiting guests. This encourages the main conversation to stay central to the room, while allowing all subsystem leads, seated in the four surrounding tables, to participate as needed.

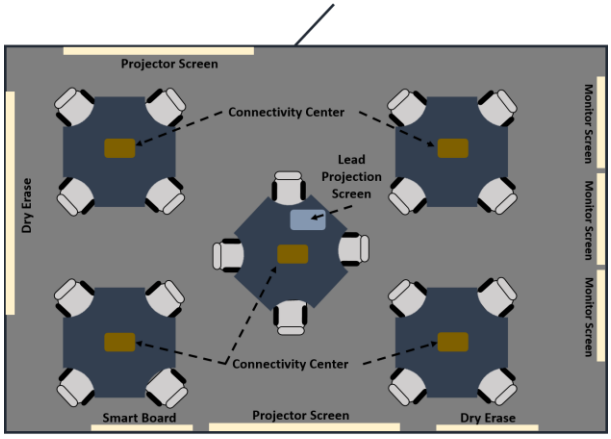

Figure 4. Compass Lab layout, designed to improve communication between team members.

Additional seating is provided along one of the walls for overflow capacity, and for any visiting students or interns. There is a secured server room as well, which also houses the team's 3D printers.

A new building is currently under construction on the center at NASA Glenn. An updated space for the Compass Lab is contained in these new building plans. This new Compass Lab will share many of the same underlying features, but with improved connectivity, better video conferencing capabilities, and a separate breakout room for splinter meetings. The current global pandemic has pushed the completion of both the building and the new lab space out a few months, but next year, the team plans to move into the new space.

6.2 Room Hardware

The team makes use of two projectors, three very large monitor screens, and a SMARTBoard®, distributed across three walls. This allows the shared information, including the Master Equipment List (MEL) and CAD layout, to be seen easily from any point in the room.

The room's video conferencing equipment is rarely used, since customers are typically on-hand. However, some customers may call in to the room's audio and follow the design on the Team Lead's shared screen via Cisco Webex™. Any team member can share their screen with others in the room by making use of the Barco ClickShare® software and hardware.

The primary server and its backup are located elsewhere on the center campus to meet GRC Information Technology (IT) security requirements. The current facility uses shared laptops and external monitors rather than fixed workstations, the only exception being for the CAD desktop machine. Peripherals, other than monitors, are also available to the team as needed, such as external keyboards, mice, and the required adapters.

In recent years, the Compass Team has added the capability to produce three-dimensional examples of these paper designs, through the use of multiple 3D printers. These are used to print 3D models of the Compass Team designs, which can be useful for customers to explain results to their management. While this additional product was created in collaboration between the configuration seat and the Compass Team lead, this proved difficult to fit into a standard design study. Operation of these 3D printers and completing the backlog of design print jobs has become the responsibility of a summer intern college student, selected each year. The team has found these products extremely useful in generating excitement and managerial buy-in.

6.3 Computing Hardware

Most subsystem leads bring their primary work laptops to the room with them to perform their analysis and complete the designs. For individuals with desktop computers, a shared laptop is provided for them, which remains in the Compass Lab. For the CAD workstation, a desktop computer is provided. Team members use both Windows® and Mac® operating systems, so the lab is designed to be compatible with both and shared laptops are available on both.

7. SUMMARY OBSERVATIONS

With direct customer interaction, an outstanding pool of team members, continual support of management, robust tools such as GLIDE, and facilities and processes conducive to concurrent engineering, the Compass team has been able to deliver over 200 conceptual spacecraft designs over the last 14 years. Its customer base has grown to include most NASA centers, other US government agencies (including the Defense Advanced Research Projects Agency [DARPA], the Navy and the Air Force), universities, as well as commercial and foreign entities such as the European Space Agency (ESA) and the German Aerospace Center (DLR).

Ultimately the key to Compass's success has been the ability serve the customer using a quick, face to face process with people able to work quickly and creatively. During the COVID-crisis this ability has had to move 'on-line' but has shown to be just as valuable if not more so. The Compass team looks to many more years of designs using our new facility and a new generation of engineers and customers

8. ACKNOWLEDGEMENTS

As is keeping with the theme of the Compass team as a whole, this paper would not be possible without the support and contributions of a great many people throughout the years. The authors wish to thank their management, Derrick Cheston the director of, and Frank Gati, the deputy director of the Systems Engineering Division. Without their support through the years, this team's existence would not be possible. Special thanks to Lee Jackson, the recently added Compass editor, for taking our original draft and crafting a well written version. Last but not least, thank you to the Compass team members. Without them nothing of the last almost fifteen years would be possible. There have been many who have come through the team through the years, too many to list in this paragraph, but we appreciate each and every one, whether they stayed for the long haul or worked one study and moved on to other things. In the end, it is really all about the people.

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