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Software User's Manual to follow.

Dynamic Resectorization and
Coordination Technology (DIRECT)
Research Study

AN EVALUATION OF AIR TRAFFIC CONTROL COMPLEXITY

FINAL REPORT

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TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

1.0 SUMMARY

A number of studies have been conducted in an attempt to understand the complexity involved in handling an Air Traffic Control (ATC) situation. These studies have typically based their measurement of complexity primarily on the level of physical workload required by the Air Traffic Specialist. Unfortunately, many of these studies do not consider the cognitive requirements placed on the Controller, simply because this information is not easily measured. As the aviation community moves towards a "free flight" environment, the complexities associated with ATC may not necessarily increase or decrease, but they will most certainly change. Because this proposed free flight environment will place the Controller in more of a monitoring role, the cognitive complexity associated with the Controller's task will further change. Complexity, as it is perceived by the Controllers (who will still be ultimately responsible for traffic separation) will become increasingly more important to understand. It is our position that an evaluation and understanding of the current and future ATC complexity would be best achieved through an analysis of the cognitive tasks of the Controller (i.e., strategies and decision making activities), and that of complexity may not be accurately reflected through measures of physical workload alone.

We begin this report with a description of some of the key results obtained from our examination and evaluation of ATC complexity. Following these detailed findings, we will describe the supporting analyses and analysis methods used to obtain these results. These analyses were based on a framework for developing and evaluating a model of the perceived complexity of an air traffic situation with specific regard to the traffic characteristics that impact the cognitive abilities of the Controller. To a great extent, this framework does not depend on any specific type of procedures for ATC and can therefore be used to evaluate complexity in both current and future ATC environments. However, for the current study, we do assume that airspace is sectorized, as it is in today's system.

Results of our study include the identification of the various characteristics, or factors, of an air traffic situation that impact the cognitive complexity of control, a complexity algorithm which incorporates the relative and absolute weightings (assigned by Controllers during Focus Group sessions) of these factors, and the evaluation of this complexity algorithm as presented in a number of Controller-In-The-Loop simulations under both current and "free flight" procedures.

Next, we present a description of how our initial complexity measurement was formulated. As well, we describe the iterative process we used to refine the measure to more closely represent Controllers' perceptions of complexity. These complexity measure modifications were primarily based on the results obtained during the simulation sessions and on the results of analyses of the complexity measure as applied to recorded live traffic situations.

With the completion of the development of the complexity measure, we are able to describe the analysis of recorded traffic scenarios with the complexity measure. This analysis evaluates the differences in complexity between air traffic being conducted under current, clearance-based procedures, and future free flight procedures.

Following the description of the complexity measure, the use of the measure is explored through discussions about a proposed Dynamic Resectorization and Coordination Technology (DIRECT) System. The focus of this system would be to provide Air Traffic Management personnel with a tool to evaluate future traffic patterns, based on the expected complexity of that traffic. The tool would also suggest various complexity reduction strategies, ranging from the restructuring / redirecting of aircraft streams to the dynamic restructuring of sector airspace. The implications and requirements for employing such a tool are also presented.

To date, Wyndemere is the only known group to have conducted real-time, Controller-in-the-loop simulations of a free flight system. Therefore, in addition to the complexity measure results, we

will present a short summary of comments made by Controllers during these Controller-in-the-loop simulations. The statements presented will no doubt be of particular interest to researchers and developers currently working towards transforming the current ATC system to meet the demands of the future.

Finally, we present a review of previous studies' attempts at measuring complexity and a justification for why more emphasis needs to be placed on understanding the cognitive aspects of control, as in the current study.

2.0 INTRODUCTION

The motivation to develop and evaluate a model of air traffic complexity comes from the recent introduction of the "free flight" concept and procedures for ATC (RTCA, 1995). Many descriptions of the free flight system state that safety will not be compromised. To ensure safety in any complex system, it is necessary to understand the impact of any major changes in system procedures on the operators of that system. This understanding will enable us to develop procedures which will maximize system benefits (in terms of safety and cost) without physically and/or mentally overloading the operators responsible for that system.

The basic premise of free flight is that Pilots can choose the most direct (and presumably optimal) flight paths to reach their destinations (RTCA, 1995). Under this definition, normal separation assurance and traffic routing will be the responsibility of the Pilots, while the Air Traffic Specialists will assume a more passive, monitoring role. However, Air Traffic Specialists will still be expected to assume control under certain conditions.* The question is whether or not the specialists will be able to easily and effectively intervene when needed. The answer depends, in part, upon the complexity of the situation and the capabilities and limitations of the specialist.

Other incarnations of free flight may not necessarily restrict the Controller to assume a primarily monitoring role as some interesting work has detailed some difficult problems associated with requiring a system operator to quickly transition from monitoring a complex system to actively controlling that system (Endsley & Kiris, 1995). In any case, the fact remains that the overall complexity of the future ATC system will change. Indeed, it is likely that *new* complexities will also be realized. These complexities will exist both in the structure of the ATC environment and in the structure of the traffic itself. In order for us to move towards the best design for a future ATC system, it is important to be able to understand the current complexities, the expected changes in those complexities with the introduction of the future system, and the impact that those changes could have on the human operators of that system.

The complexity of air traffic control is influenced by many factors, including the abilities of each specific Controller, the equipment available, and the complexities of the ATC environment itself. While all of these aspects of complexity are important to understand, they are quite large in scope. In order to focus our study we define our measure of complexity based on the air traffic situation itself. Therefore, in our evaluation of ATC complexity, we focus on the events or factors in a traffic situation that impact the Controller's physical and cognitive processes required to maintain a safe and efficient flow of traffic.

In this paper, we will describe our framework for evaluating and measuring the complexity of ATC. The framework was designed to help us determine and evaluate a model of the perceived complexity of an air traffic situation, with specific regard to the traffic and airspace characteristics that impact the cognitive (problem solving, strategy formulation) and physical (communications, etc.) demands placed on the Controller. Controller input to the definition of complexity was essential, due to their extensive amount of knowledge of the domain. Consequently, this called for expert Air Traffic Specialists to be used in identifying and evaluating complexity factors and to participate in simulations designed to further develop the complexity measure. Although our evaluation framework does not necessarily depend on any specific type of ATC procedures, initial work has been directed at understanding complexity under current ATC procedures. Once our model of complexity has been tested and verified under current ATC procedures, it may be used to examine the impact that free flight procedures might have on the Controller, with possible additional modifications.

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* As proposed, Controller intervention will only occur when: (1) tactical conflict resolutions are needed, (2) flow management requirements for busy airports need to be satisfied (3) resolution of unauthorized special use airspace (SUA) entry is needed, and (4) flight safety violations are imminent.

This rest of this report is organized as follows: First, we will present the detailed findings from our examination and evaluation of ATC complexity. Results of our study include the identification of the various characteristics, or factors, of an air traffic situation that impact the cognitive complexity of control, and a complexity algorithm which incorporates the relative and absolute weightings (assigned by Controllers during focus group sessions) of these factors. Additional development of the algorithm was based on an evaluation of the algorithm as presented in a number of Controller-in-the-loop simulations under both current and free flight procedures, and the modifications made to the complexity algorithm based on these findings. These analyses were based on an evaluation framework and consequently, the framework will also be described.

With the completion of the development of the complexity measure, we are able to describe the analysis of recorded traffic scenarios with the complexity measure. This analysis evaluates the differences in complexity between air traffic being conducted under current, clearance-based procedures, and future free flight procedures.

The use of the validated complexity measure is explored through discussions about our proposed Dynamic Resectorization and Coordination Technology (DIRECT) System. The focus of this system is to provide Air Traffic Management personnel with a tool to evaluate future traffic patterns, based on the expected complexity of that traffic. The tool would also suggest various complexity reduction strategies, ranging from the restructuring/redirecting of aircraft streams to the dynamic restructuring of sector airspace. The implications and requirements for employing such a tool are also presented.

In addition, we will also present a review of other techniques that have been used for measuring complexity. Previous studies have focused on the measurement of physical actions as an indication of ATC complexity. However, because a Controller's mental processes are also heavily impacted by increased complexity, some illustrative examples are presented which support the argument that measures of physical processes alone are not enough in order to fully understand the complexity of ATC. This section will also describe some of the difficulties associated with evaluating and measuring mental processes. This background data serves to provide a justification for why more emphasis needs to be placed on understanding the cognitive aspects of control, as in the current study.

Finally, study conclusions and appropriate references will be included. As further support of the current study effort, we will discuss some additional interesting findings which may suggest the need for further research into the complexity of air traffic control and the impact that free flight may have on Controllers.

3.1 Individual Complexity Factors

The table below shows the individual factors that are being computed in the complexity algorithm. These factors were identified through a number of efforts including literature reviews, Controller interviews, exploratory simulations, and Complexity Focus Group sessions. In addition to the individual complexity measures, an overall complexity measure is also computed. Complete descriptions of each of these efforts are presented in Chapter 4.0, Supporting Analyses / Analysis Methods.

Aircraft Count	[ACT]
Angle of Convergence in Conflict Situation	[ANG]
Number of Aircraft Climbing or Descending	[CoD]
Distribution of Closest Points of Approach	[CPA]
Aircraft Density	[DNS]
Level of Knowledge of Intent of Aircraft	[INT]
Neighbors	[NBR]
Proximity of Aircraft to Sector Boundary	[PRX]
Proximity of Potential Conflicts to Sector Boundary	[PRX-C]
Airspace Structure	[STR]
Variance in Aircraft Speed	[VAS]
Variance in Directions of Flight	[VDF]

Table 1. Individual Factors Used in Complexity Algorithm

3.2 The Complexity Algorithm

The overall complexity algorithm, which has been developed, verified, and validated using the methods described in this report, is presented below. A complete description of the experimental design used to develop this algorithm is presented in the next chapter.

The final complexity algorithm:

0.0172 x ACT (MAX., 10.0)

0.328 x DNS (MAX., 10.0)

0.0498 x CPA (SUM, 15.0)

0.1070 x ANG (SUM, 15.0)

0.0426 x NBR (SUM, 15.0)

$$
\begin{array}{r}
0.0754 \times \text{PRX-C (SUM, 15.0)} \\
0.1134 \times \text{CoD (SUM, 15.0)} \\
0.0709 \times \text{VDF (MAX., 10.0)} \\
0.0 \times \text{VAS (MAX., 10.0)} \\
0.2 \times \text{PRX (SUM, 10.0)} \\
0.0676 \times \text{STR (MAX., 10.0)} \\
+ \quad 0.2564 \times \text{INT (MAX., 10.0)} \\
\hline
\textbf{OVERALL COMPLEXITY}
\end{array}
$$

Figure 1. The Complexity Algorithm

This overall complexity algorithm is a weighted sum of contributions from individual complexity factors as described above. Each of the complexity factors contributes to the overall complexity through either a maximum (MAX.) function or a summation (SUM) function. A weighted sum (WEIGHT) function is also available, but was not used in the final complexity algorithm. Each complexity factor is shown in the algorithm above as a function of the contribution type, MAX. or SUM, and the look-ahead time, in minutes, over which the contribution function is applied. The procedures used to define this algorithm will be described in more detail in further sections of the report.

3.3 Traffic Complexity Analyses - Current Procedures Vs. Free Flight

The density and the number of closest points of approach associated with current procedures and free flight were compared on a sector-by-sector basis across 15 minute time intervals (for these comparisons, the TRACON was considered to be one sector). A count was made of all cases in which the current procedures complexity was higher and cases in which the free flight complexity was higher. The results from a 6 hour System Analysis Recording (SAR) data sample are shown below. These results are accumulated over sectors and time intervals. Note that these results may not represent the same sets of sector measurements because cases in which the complexity does not change were ignored.

	CP > FF	FF > CP
DNS	293	274
CPA	344	338

Table 2. DNS and CPA Comparison - Current vs. Free Flight

Also note that a similar result is obtained here as in a previous study conducted by the FAA and The MITRE Corporation (Ball, DeArmon, and Pyburn, 1995). Both studies indicate that the free flight procedures decrease sector density and conflict events as compared to current procedures.

A comparison of the overall complexity between current procedures and free flight was also conducted. These results, again accumulated over sector and time intervals, are presented below.

	CP > FF	FF > CP
Overall	145	971

Table 3. Overall Complexity Comparison - Current vs. Free Flight

The results of this comparison indicate a substantial increase in the number of cases in which the overall ATC complexity is greater under free flight than under current procedures. Note that many more cases are involved in the comparison of overall complexities than in the comparisons of density and conflict events. This is caused by the fact that many more traffic characteristics are considered in the overall complexity measure, which results in fewer situations in which the complexity remains the same between current procedures and free flight.

This result provides a very strong indication that measures of density and conflict events are not sufficiently representative of the overall complexity of ATC. The differences in traffic characteristics - other than density and conflict events - have a significant impact on the difference in overall complexity between current procedures and free flight.

3.4 Complexity Reduction and the DIRECT System

A number of complexity *reduction* heuristics have been identified in this study. These heuristics can be grouped into two major classes, based on the ATC element (air traffic or sector) affected. Heuristics that affect the air traffic itself include:

- Sector Avoidance
- Changing Conflict Geometries
- Creating Aircraft Streams (speeds, headings, or climbing/descending aircraft)
- Moving Conflicts.

Heuristics that affect the structure of the airspace include:

- Temporarily Moving Sector Boundaries
- Increasing Airspace
- Changing the Sector Shape.

Both of these classes of heuristics can be used *in conjunction* to provide Air Traffic Specialists with an optimal solution to various traffic problems. The DIRECT System project is intended to provide Air Traffic Specialists with both a "Dynamic Resectorization" *and* a "Coordination Technology" tool. Using this system, we believe Air Traffic Specialists will have the appropriate information and assistance needed to reduce the complexity placed on Controllers, to maximize the use of airspace, and to allow more aircraft to fly under free flight procedures. Further discussions about the use of these heuristics, and the benefits of the DIRECT System are provided in section 5.3.

4.0 SUPPORTING ANALYSES / ANALYSIS METHODS

4.1 The Evaluation Framework

4.1.1 The Challenge of Applied Experimentation

Today, many applied psychological experiments deal with the problem of trying to understand a large range of human-machine systems. These studies themselves can differ in complexity, from studying how an operator manipulates menus of a window-based word processing system to how a Controller effectively manages and controls air traffic. Whatever the focus of study, there are some fundamental problems with traditional methods of experimentation. As the human-machine system under study becomes more complex, these problems become more difficult to overcome.

The main reason for performing an experiment is to be able to generalize what was learned in the experimental setting to some target setting. However, given the highly complex nature of some types of human-machine systems (such as Air Traffic Control), this goal of generalizable results is often difficult to obtain. What we have seen in the past, in terms of traditional psychological experiments, may not suffice as a solution to this problem. For example, classical research methods (wherein the experimenter manipulates an independent variable and measures the resulting change in the dependent variables) do not always take into account the many interdependent relationships that exist between elements in a complex system.

It is suggested that a greater understanding of the target work domain, along with a more careful selection of subjects and tasks, is needed to better represent the operational setting of interest, and that doing so will increase the validity of these generalized results. Our evaluation framework is based upon these suggestions and depends greatly upon participation from current Air Traffic Controllers.

Understanding systems of increasing complexity necessitates that new, more complex methods of analysis be used in order to handle the many possible interactions that can occur. Also, when studying complex systems, it can become increasingly difficult to interpret results. Our evaluation framework was designed so that it could be used to create an experimental design that addresses the challenges described above. In using this framework, we believe that we will be better able to achieve valid, generalizable results.

4.1.2 Work Domain Expertise

One of the most important contributors to the usefulness of any research effort is a thorough understanding of the work domain under study. This understanding not only aids in identifying issues for study, but it also provides a baseline from which to begin analyzing experimental data and interpreting the results. Although this understanding of the work domain can be accomplished through many different methods, a trade-off does exist (i.e., increased amount of time, personnel, etc.).

Therefore, the best and quickest way for us to uncover the detailed complexities associated with air traffic control was to substantially involve Air Traffic Controllers in our study. From a time-investment perspective, including classroom work, most en-route Controllers reach Full Performance Level (FPL) status within 3-4 years. Terminal Controllers may take 5 to 6 years to reach FPL status. The number of years required to be considered an FPL Controller reflect the complex nature of the Controller's job and provide support as to why we cannot simply rely on our own knowledge of ATC as a basis for understanding the complexities of the work domain. Indeed, any study intended to examine the complexities of air traffic control *must* include input from experienced, FPL Controllers. Without this input, it is highly likely that the subtleties of the work domain will not be investigated, and the resulting data will not be very representative of the real world system.

Methods to obtain Controller input are quite varied in nature, and each method has certain benefits and limitations (*cf.* Mogford, Harwood, Murphy, and Roske-Hofstrand, 1994). Possible methods we considered for use in our study included the collection of questionnaire data, unstructured group discussions, various protocol techniques, structured interviews, and simulations. These methods were chosen because they are non-intrusive to actual ATC operations, are preferred by experts as being meaningful ways to elicit information, and in most cases allow direct access to Controller knowledge structures and cognitive processes (Mogford, et al., 1994).

4.1.3 Representativeness of Simulations

The concept of designing psychological experiments to more closely represent the target operational setting is embodied by Brunswik's idea of *representativeness* (Brunswik, 1956). Representativeness is achieved when you present the participant with an experimental situation that captures the relevant aspects of a corresponding real-life situation. The closer the design of the experiment is to the situations found in the actual operational setting, the more we can assume the results will be able to be generalized to that target concept. Brunswik (1956) also tells us that, in classical psychological experimentation, "all relevant external conditions are to be systematically controlled, and that all internal conditions are to be treated quasi-systematically by computational elimination of random variability." However, in the target operational setting (for example, the real-world ATC environment), this type of situation rarely exists because of the natural interaction of related and non-related variables and other factors influencing participants' behavior and performance. Therefore, complex system studies should be designed so that they capture these interactions, and other influencing factors, in order to obtain a high level of representativeness.

One type of experimental situation that can present the subject with realistic representations of complex human-machine interactions is the use of simulators (Sheridan and Hennessy, 1984). As mentioned above, complex human-machine systems obviously cannot, by definition, be addressed by simple stimulus-response experiments. Therefore, we must look towards more complex experimental designs, which may involve simulations. Various types of simulations can be built to capture the relevant aspects of the target situation of interest, and such simulations can provide us with methods to study complex behavior without being intrusive to the operators of the actual target situation. Although these simulations can increase the observability of a system (Brehmer, 1990) and are potentially better for achieving a certain level of representativeness, increased simulator complexity (increased representativeness) corresponds to an increase in cost, time, and the difficulty associated with interpreting the results. The ultimate level of representativeness, of course, comes from studying the actual operational setting. However, Sheridan and Hennessy (1984) tell us that using simulations (full-scope or otherwise) is one of the best ways to study complex situations, as these simulations can best be used "to identify critical questions that later can be addressed in the much more expensive, time-consuming and complex studies in operational settings."

Our goal, then, was to provide a simulation environment that represents the real-world ATC system as much as possible. In order to do so, it was determined that possibly one of the most important aspects to simulate was the communication between Controllers and Pilots. The simulation system used in this study (the Pseudo Aircraft System (PAS) developed by Syre, a subsidiary of Logicon) utilizes Pseudo-pilots at computer workstations. In order to simulate the communications aspect of ATC, the Pseudo-pilots communicated with the Controllers via headsets. The Pseudo-pilots received voice clearances and instructions from the Controllers and entered the clearances into the simulation system. The system then simulated the dynamic response of the aircraft to the entered clearance. In addition, the aircraft locations were presented to the Controllers on a workstation display that very closely resembles an actual Controller radar display. We believe that the increased representativeness of this aspect of the environment enabled us to more closely simulate a real-world ATC system than would a situation in which the Controllers did not experience Pilot interaction.

4.1.4 Complexity of Measurement

The increased complexity of our experimental design translated into an increased complexity associated with the analysis of our results. Taking into account the many different factors and disturbances that can be present in a complex system such as ATC, we were certain to see different subjects perform in many different ways. It has been stressed by many that in order to analyze a subject's performance on a certain task, it is of primary importance to analyze the *context* of the situation in which the control action/decision took place (Sheridan and Hennessy, 1984; Brehmer, 1990; Brunswik, 1956; Moray and Rotenberg, 1989; Sanderson, Verhage & Fuld, 1989). Further, Brunswik (1956) states that when the complexity of the task and experimental setting under study is increased, the complexity of measurement methods must be increased accordingly. Given these suggestions, it was highly unlikely that traditional analysis methods, such as statistical measurements, would be suitable for understanding our collected data. Therefore, we attempted to utilize statistical data in our analyses, where appropriate. However, we are reminded by Mogford, et al. (1994) that statistical techniques cannot provide us with direct access to Controller cognitive processes, which was a fundamental goal of this study. In addition, Mogford, Murphy, Roske-Hofstrand, Yastrop, and Guttman (1994b) found that there was a high degree of correspondence between direct methods (such as questionnaires, interviews) and indirect methods (paired comparisons between factors) of identification of complexity factors. Therefore, we concentrated our analyses on the interview data, which provided a great deal of context within which to understand the collected data.

4.2 Experimental Design

The description of the experimental design used for the study is organized as follows: First, a list of initial complexity factors, identified by the researchers at Wyndemere, will be presented. This list will be followed by a description of the initial, exploratory simulations conducted to uncover any additional factors which could also be used in the final complexity measure. To further develop the complexity measure, a Traffic Management Coordinator (TMC) from the Denver Air Route Traffic Control Center (ARTCC) facility was interviewed. The information gained from this interview, as well as the manner in which it was obtained, is described. Next, a description of the "Complexity Focus Group Sessions" will be presented. This group consisted of a number of FPL Air Traffic Specialists, of varying levels of experience and from different control areas within Denver ARTCC, tasked to help fine-tune the weightings assigned to the complexity factors used in our measure. A description of how these weightings were assigned will also be given. Finally, we will describe the validation of our complexity measure through simulations.

4.2.1 Identifying Initial Complexity Factors

The researchers at Wyndemere have extensive hands on experience working in operational ATC facilities. For example, in developing air traffic control automation tools, Wyndemere staff have spent many hours working with Controllers, traffic management specialists and other FAA personnel in various ARTCC facilities and Terminal Radar Approach CONtrol (TRACON) facilities. Many Wyndemere staff members have also attended full Controller training courses at ATC facilities in order to gain or maintain an in depth understanding of the operations at a given facility.

Researchers at Wyndemere, relying on their experience in air traffic control procedures, airspace design and adaptation, air carrier operations, systems engineering, systems optimization, and airspace, route and trajectory analysis, held a number of meetings designed to identify a set of initial complexity factors that would be meaningful to include in a measurement of air traffic complexity. Input to these meetings also included reviews of existing studies and various ATC manuals, which provided a background of information that could be used as a basis for identifying complexity factors. These meetings resulted in the identification of a number of factors believed to influence the perceived level of complexity of an air traffic situation. These initial complexity factors are presented below, in Table 4.

Level of Knowledge of Intent of Aircraft (INT)	Variance in Directions of Flight (VDF)
Special Use Airspace (SUA)	Performance Mix of Traffic (PRF)
Weather Effects On Airspace Structure (WST)	Number of Aircraft Climbing or Descending (CoD)
Weather Effects On Aircraft Density (WDN)	Distribution of Closest Points of Approach (CPA)
Aircraft Density (DNS)	Angle of Convergence in Conflict Situation (ANG)
Proximity of Potential Conflicts to Sector Boundary (PRX)	Variance in Aircraft Speed (VAS)
Number of Crossing Altitude Profiles (CAP)	

Table 4. Initial Complexity Factors, Identified by Wyndemere Researchers

4.2.2 Exploratory Simulations

In order to identify additional complexity factors, a number of simulations were held at Wyndemere. For these simulations, current FPL Controllers participated in a real-time, Controller-in-the-loop ATC simulations of both current and free flight procedures. For simulation purposes, "free flight" was defined as having each aircraft fly a direct route from its departure airport to its destination airport.

In the exploratory simulation sessions, the Controllers were presented with two scenarios that use current flight procedures and two scenarios that use free flight procedures, as defined above. The scenarios were designed for a single sector simulation utilizing a high altitude sector in the southern region of Denver ARTCC. Controllers were given flight strips for each of the flights in the scenario. These flight strips indicated an airway-based route of flight for the current procedure scenarios and a direct route of flight for the free flight scenarios. The Controllers were asked to 'think aloud' as they made their decisions on how to deal with the traffic situation (Ericsson & Simon, 1984, Sanderson, et al., 1989; Sicard and Siebert, 1987). Throughout the simulations, a number of researchers were present, and the Controllers were asked numerous questions regarding their plans for action, the goals identified for these plans, and justifications for certain behavioral patterns. However, this interference from researchers was considered appropriate during the exploratory simulations due to the fact that the exploratory simulation environment was not as highly structured or as time critical in nature as the real-world ATC domain. Verbal protocol data was collected along with researcher comments on the thoughts and plans expressed by the Controllers during all simulation sessions. Additional data recording was handled by the PAS simulation system. Finally, after each scenario, the Controller was asked to assign a rating to the scenario as to how difficult the scenario was to control, considering both safety and efficiency.

Although the simulations were relatively informal, a number of interesting initial results have been identified. Some of these results lend support to the expected increase in complexity that might be experienced under free flight procedures, and also provide some support for our initial complexity factors. As well, the simulations served to support our belief that the complexity of air traffic control cannot be simply based on the measurement of physical actions alone. An example of this support is presented below, in our describe one of the simulation scenarios.

The first plot below (Figure 2) shows the latitudinal / longitudinal flight paths that would be followed by aircraft in one of the free flight scenarios, if no maneuvers were instructed or executed to avoid the conflicts. This scenario was designed to be the most complex free flight scenario with almost all of the aircraft in the scenario approaching a very small area of airspace at the same time.

However, Figure 2 leaves out two critical dimensions of the four dimensional scenario--altitude and time. This particular scenario presented all aircraft at flight level 350, so it is not necessary to show a graph of aircraft altitudes. Still, the conflict situations cannot be properly identified without a representation of the time dimension. Figures 3 and 4 show the longitudinal and latitudinal coordinates of each flight as a function of time, respectively.

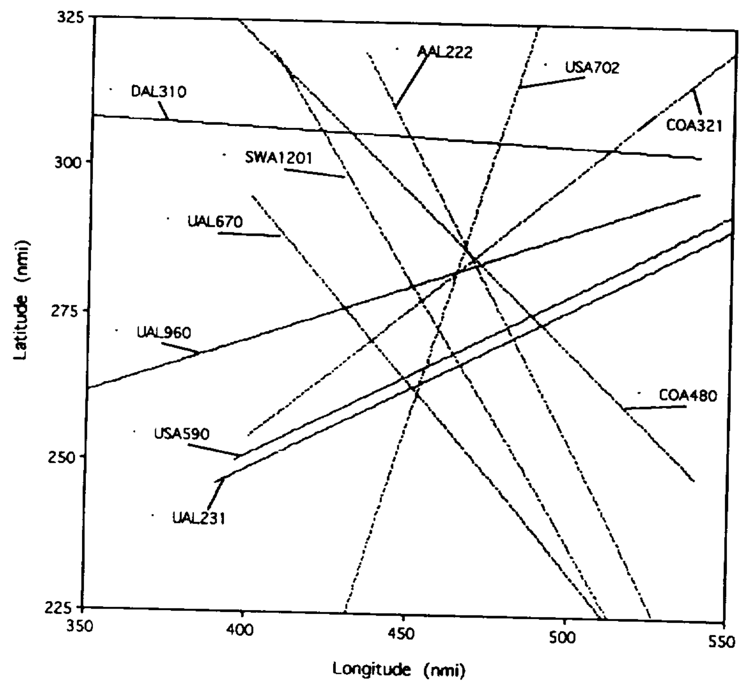

Figure 2. Lat / Long Flight Tracks of Aircraft Under Simulated "Free Flight" Procedures

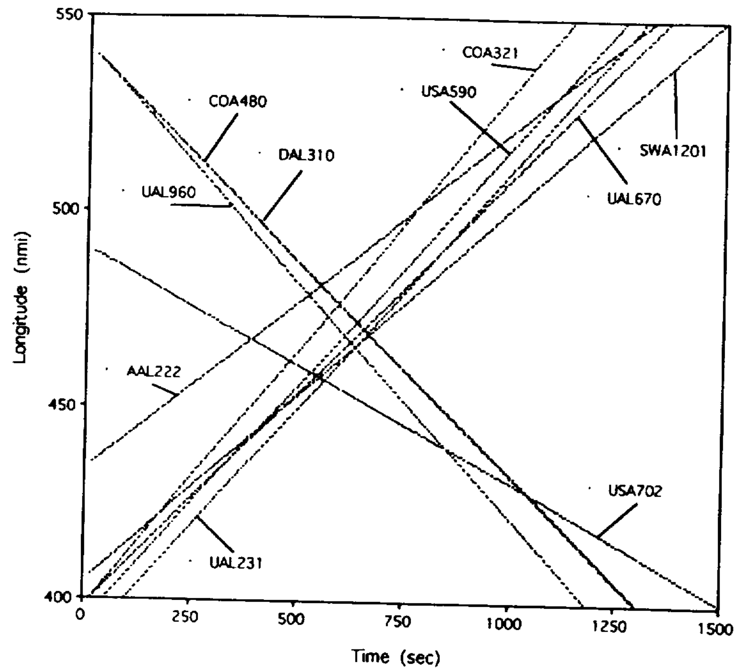

Figure 3. Longitudinal Position vs. Time for Simulated "Free Flight" Aircraft

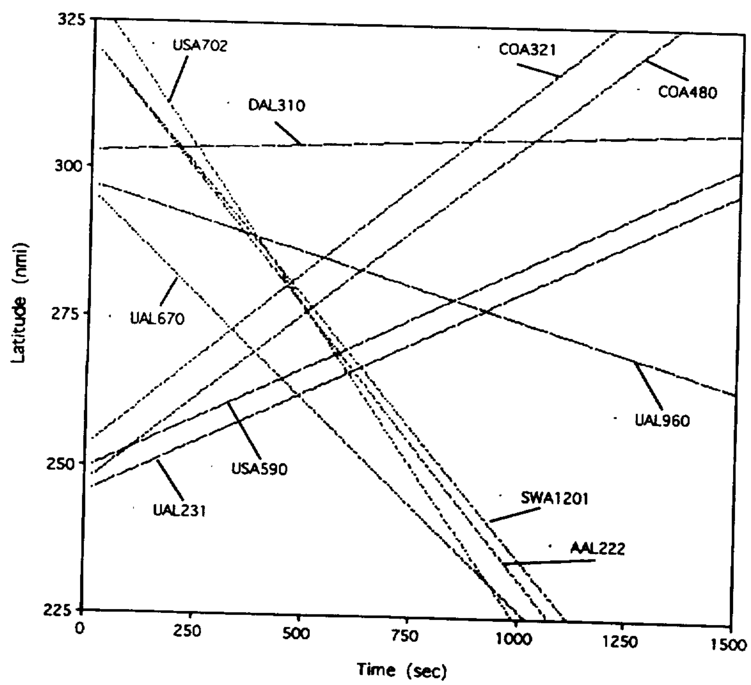

Figure 4. Latitudinal Position vs. Time for Simulated "Free Flight" Aircraft

Note that many aircraft were within 5 miles of an (x) position of 470 miles (Figure 3) and a (y) position of 285 miles (Figure 4, below) from the coordinate system origin, approximately 8 minutes into the simulation. According to the Controller participants, the density of traffic in this simulation was judged to be fairly high, and impacted the complexity of the situation.

Figure 5 shows the same scenario as controlled by one of the simulation subjects. Again, the plot shows the latitudinal/longitudinal positions of each aircraft. Of interesting note in this scenario is the fact that the Controller used only 15 vectors to resolve the conflicts within a 10 minute time period. As discussed above, it is clear that the physical task time required for the Controller to implement his plan was not excessive-a fact that supports our claim that measures of physical task time alone are insufficient indications of complexity.

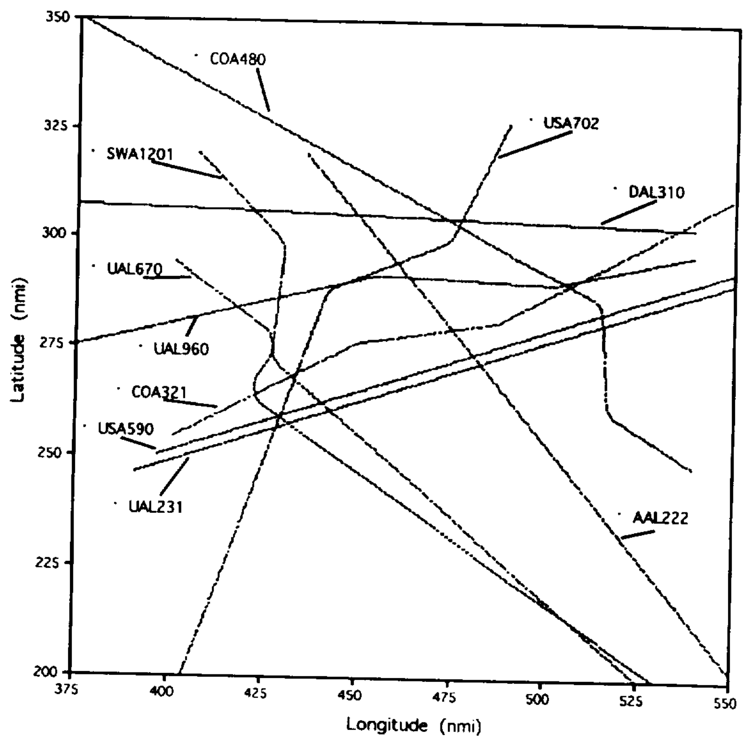

Figure 5. Lat / Long Flight Tracks of Aircraft With ATC Commands Issued

Figures 6 and 7 show the longitudinal and latitudinal coordinates of each flight, as controlled, as a function of time. From a procedural standpoint, it is important to notice that UAL670 and COA321 were within 5 miles of each other at approximately 314 seconds into the simulation.

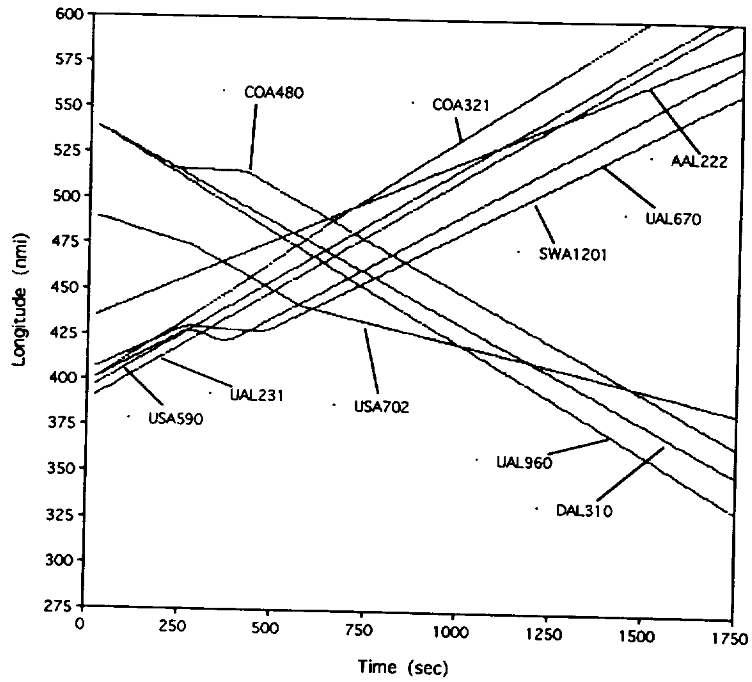

Figure 6. Longitudinal Position vs. Time for Controlled Aircraft

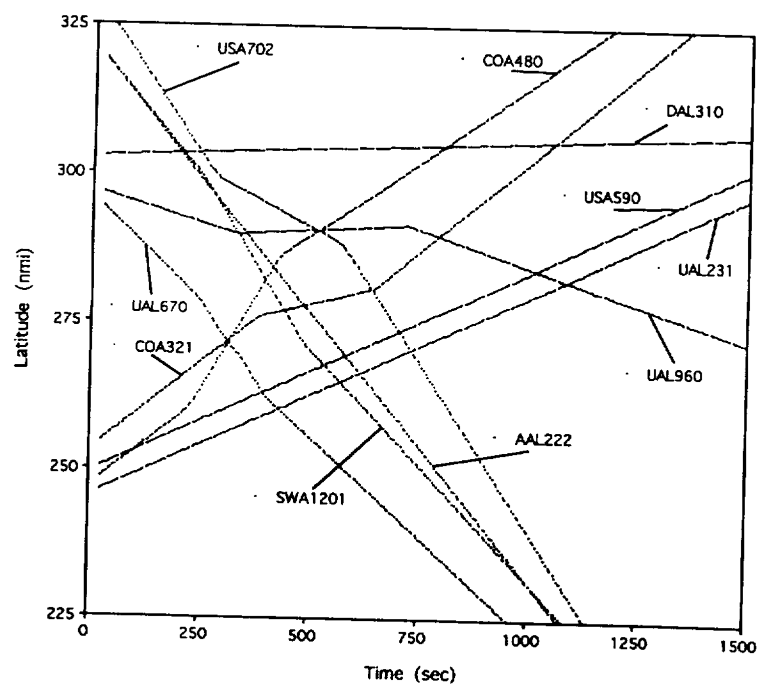

Figure 7. Latitudinal Position vs. Time for Controlled Aircraft

The fact that the Controller subject allowed these two aircraft to violate the minimum acceptable separation requirement may have been the product of the simulation environment itself. Since most Controllers are not required to provide protocol data during real-world operations, they were not entirely practiced at doing so for our simulation purposes. However, as mentioned above, these were merely exploratory simulations and the key to the success of these simulations was to understand as much as possible about what the Controller was doing and thinking while controlling traffic.

An additional interesting result of the exploratory simulations was the significance that Controllers placed on the knowledge of intent, or lack thereof, of the aircraft. In simulation debriefings with the Controller subjects, they felt that a strong increase in the level of complexity of the traffic situation would result if the aircraft were to actually maneuver on their own. As stated by the RTCA white paper, free flight aircraft will have the flexibility of VFR flight while being offered IFR protection (RTCA, 1995). However, since the Pseudo-pilot was controlling as many as twelve aircraft, it was not possible for the Pseudo-pilot to determine what maneuvers would be realistic for each individual aircraft to make, in order to exploit that flexibility. In essence, this created a situation in which the scenario was no longer a true free flight scenario, as the Controllers were able to trust that the aircraft would not alter their flight paths without Controller clearance.

Still, the presence of an operational error (with respect to separation minima) is an interesting issue worth further investigation. The error might suggest that the Controller was operating too near the limits of his abilities. Although this might have been confounded with the verbal protocol procedure, the high level of complexity of the scenario may have left very little mental resources available to provide this verbal protocol data along with acceptable control performance.

4.2.3 Critical Decision Interviews

In an attempt to verify our complexity factors for inclusion in a complexity measure, as well as to gain further insight to other factors which might contribute to traffic complexity (see Table 5), a Wyndemere researcher organized a meeting with a TMC from the Denver ARTCC facility. During this meeting, the TMC participated in an interview session that was based on the Critical Decision Method for knowledge elicitation, developed by Klein, Calderwood, and MacGregor (1989). In the interview, the TMC was asked to identify past scenarios that stand out in his memory due to the fact that they were high in complexity. As part of the interview, the TMC was asked to describe his goals and expectancies for each situation, the cues he used for action, the actions he took, the other available options, and the explicit factors responsible for making the scenario complex. The TMC was also allowed access to maps of Denver ARTCC airspace on which he could draw out the scenarios as he described them.

Results from the critical decision interview meeting reinforced the importance of a Controller having knowledge of the intent of other aircraft. In addition, the TMC described the complexities associated with certain air traffic situations and the impact they have on the amount of available airspace for use by a Controller. For example, from the TMCs standpoint, the primary impact that a weather cell has on a sector is the fact that a certain area of the sector is no longer available for use. In effect, the volume of usable airspace within a sector decreases in size when a weather cell is present. This, in turn, affects the overall density of aircraft distributed throughout the rest of the sector, which reduces the amount of freedom the Controller has for aircraft routing.

In addition to these factors, the TMC described the impact that multiple conflicts occurring in a short time period might have on the perceived complexity of an air traffic situation. In his accounts of previous complex scenarios, he detailed the problems associated with trying to solve multiple conflicts simultaneously. According to the TMC, the complexity results from the large time lags inherent in the system, and the fact that aircraft involved in multiple conflicts may have conflicting goals (with respect to resolution).

Airspace Structure [STR]	This measurement will examine the impact that sector structure has on the complexity of air traffic control.
Special Use Airspace [SUA]	This measure is intended to identify how the number/size/activity of restricted areas, warning areas, and military airspace impact the complexity of an air traffic scenario.
Weather Effects On Airspace Structure [WST]	Weather impacts the amount of usable airspace, and therefore the structure (size and shape) of the sector. This measure will examine the impact that a weather cell can have on the structure of a sector, and how that translates into increased complexity.
Proximity of Potential Conflicts to Sector Boundary [PRX]	An examination of the location(s) of the potential conflict(s) with respect to current sector boundaries.
Aircraft Density [DNS]	A measurement of the density of aircraft with respect to the usable amount of airspace.
Number of Facilities [FAC]	A count of the number of facilities served by, or contained within, a specific sector.
Number of Aircraft Climbing or Descending [CoD]	A simple numerical count of the number of aircraft expected to climb or descend in altitude.
Number of Crossing Altitude Profiles [CAP]	This measure is an examination of the number of ascending and descending aircraft profile *pairs* that are expected to occupy (in crossing) the same altitude within a specified period of time in the future.
Weather Effects On Aircraft Density [WDN]	Weather also impacts the density of the aircraft in the sector, because the amount of available airspace is effectively reduced. Therefore, this measure will examine the impact that a weather cell has on the density of aircraft.
Variance in Aircraft Speed [VAS]	A measurement that looks at the variability of speed tracked for each aircraft.
Variance in Directions of Flight [VDF]	A measurement that looks at the variability of direction for each aircraft to be controlled.
Performance Mix of Traffic [PRF]	A measurement that looks at the variance in performance capabilities of current and expected aircraft.
Winds [WND]	A measure of wind speed and azimuth by altitude, and its impact on aircraft performance characteristics.
Distribution of Closest Points of Approach [CPA]	This measure is a time-based distribution of the number of intersecting (laterally) flight paths which could be potential conflicts.
Angle of Convergence in Conflict Situation [ANG]	A measure that examines the predicted angle of convergence in a conflict. Shallower angles of convergence result in a longer period of potential conflict.
Neighbors [NBR]	The proximity in lat. and vert. distance between ACFT pairs in conflict and other ACFT within some parameter distance or time.
Level of Knowledge of Intent of Aircraft [INT]	A measure that looks at the effects that the knowledge of intent of an aircraft has on the complexity of a conflict involving that aircraft.
Separation Requirements [SEP]	A measure that examines the impact that imposed separation requirements for longitudinal sequencing and spacing has on complexity.
Coordination [CRD]	The impact that the presence of aircraft that require some form of coordination (with other sectors, etc.) for proper control has on the complexity of an air traffic situation.

Table 5. Complexity Factors Examined For inclusion in Complexity Algorithm

After the Critical Decision Interviews, the complete list of complexity factors was compiled and redundant factors were removed. In total, there were now 19 factors believed to contribute to the perceived complexity of an air traffic situation. These factors, including the additional factors identified through both the TMC interview and the simulations, are those listed above in Table 5. Included with this list is the short description of each factor given to each Air Traffic Specialist in the Complexity Focus Group.

4.2.4 Complexity Focus Group

The next step in our process was to assign weighting values to each of the complexity factors. In order to properly assign these weightings, we held a number of sessions in which we presented our complexity factors to 10 current, FPL Air Traffic Specialists (5 TMCs/Supervisors, 5 Controllers; all from Denver ARTCC). The Specialists were asked to rate and rank the complexity factors in a number of ways. Since the overall impact of each of the individual factors may depend on the addition of other factors, the multiplicative effects between factors and even within multiple occurrences of the same factor, if appropriate, were also examined.

During these sessions, each Air Traffic Specialists first participated in a Factor Interview, which was designed to elicit both qualitative and quantitative information, as well as to aid in establishing a "common language" between researchers and Air Traffic Specialists with respect to the definitions and assumptions associated with each complexity factor. Participants were then asked to rate both the individual factors and factor pairs in terms of their absolute level of contribution to the perceived complexity of an air traffic situation. In addition, the participants were asked to rank the factors against themselves in order to understand the relative relationships between these factors, and how these relationship affect the perceived complexity. The results from this part of the study were used to aid in assigning the weighting values of each factor for use in the complexity measurement.

4.2.4.1 Factor Interviews

Each Focus Group session began with an interview; the purpose of which was to achieve a number of goals. First, as mentioned above, the interview was designed to familiarize the Air Traffic Specialists with the definition and assumptions associated with each complexity factor. In doing so, both the researcher and the Air Traffic Specialists were better able to communicate their ideas regarding the specifics of each factor, and questions (posed by both parties) were more readily answered.

Second, the interviews were designed to elicit both qualitative and quantitative information about each of the 19 complexity factors, and the format resembled the Critical Decision Interview methodology described above. The collected qualitative information was very valuable in that it helped determine useful starting points to begin analyzing the collected quantitative data. As well, given the complex nature of the ATC system and the high degree of variance in human interaction with that system, the qualitative data was essential to truly understand the details regarding the complexity of the system. Examples of the type of data collected in these Factor Interviews include: Specifics about the range of parameter values (of each factor) that impact complexity, a time frame in which to view the impact of this factor on the complexity of control, and dependencies of a specific factor on other elements of air traffic control.

Complete summaries of the results from the Factor Interviews are presented in Appendix B. However, an example of this data is presented below. This example is a summary of the comments regarding the impact that the number of aircraft expected to be climbing or descending [CoD] has on the complexity of control.

In general, Controllers agreed that an increase in the number of aircraft climbing or descending within a sector results in an increase in the complexity associated with the control of that sector. However, the relationship between the number of aircraft climbing or descending and complexity depends on the density of aircraft, the number of conflicting altitude pairs, the intentions of the aircraft, and the type of sector being worked. The answers given in the interviews were given with the assumption that the Controller was working an overflight sector, and some existing condition was forcing the aircraft to have to climb or descend. In general, however, most Controllers stated that if they were controlling an arrival or departure sector, then the impact of an increase in the number of aircraft climbing or descending wouldn't be as great as if they were working an overflight sector.

When asked to give a range of the number of aircraft climbing or descending that they consider to be very high, high, and low in complexity, most answers were given in terms of the percentage of the total number of aircraft. Obviously, then, these numbers depend on the total number of aircraft within the sector (the density of the aircraft). Therefore, Controllers assumed "moderate" levels of traffic when stating their answers, presented below.

	μ	$\sigma^{(n-1)}$
Very High	>52%	14.6
High	>31%	8.6
Low	<23%	6.5

In addition, one Controller mentioned that as the percentage gets closer to 100, it actually becomes slightly easier again because in that situation, every aircraft is behaving in the same general manner.

With respect to time, Controllers feel that looking ahead about 15 minutes is reasonable to determine the impact that climbing or descending aircraft will have on the complexity of control..

Unfortunately, it is nearly impossible to effectively analyze qualitative data in a statistical manner, due to the nature of the data itself. Therefore, we also collected numerical, quantitative data through rating and ranking scales, completed by each Air Traffic Specialist, as described below.

4.2.4.2 Rating and Ranking Questionnaires

After the Factor Interviews, each Air Traffic Specialist was asked to fill out three separate rating/ranking questionnaires. The first questionnaire asked the Air Traffic Specialists to rate each complexity factor from 1 to 10, based on how strongly they felt that factor contributes to the overall complexity of an air traffic situation. For example, they were to assign a rating of "10" to any factor that they felt greatly impacts the level of complexity experienced when controlling an air traffic situation. Conversely, they were to assign a rating of "1" to any factor that they felt has very little impact on the complexity of a situation. A rating of "5" was to be given to any factor which they felt only somewhat impacts the overall complexity of a situation. Finally, they were to assign a rating of "0" to any factor that they feel has nothing to do with the complexity of air traffic control.

Results from this questionnaire are presented below. As part of our study, we asked Controllers to also consider the impact that weather has on the complexity of control. However, at the time, we did not have access to weather information to include in our simulations, so we did not measure the impact of weather in this current phase of research. In the data table of sorted absolute ratings, presented below, the weather data has been removed.

Absolute		
Factor	μ	$\sigma^{(n-1)}$
INT	7.9	2.18
DNS	7.2	2.39
CAP	7.2	2.04
NBR	6.7	2.11
CRD	6.7	2.45
CPA	6.5	1.78
CoD	6.4	2.07
SEP	6.3	1.70
PRX	6.0	1.94
ANG	6.0	1.89
STR	5.2	2.66
VDF	5.1	2.13
PRF	5.1	2.51
FAC	5.0	2.49
VAS	4.3	2.31
SUA	3.9	2.02
WND	3.2	1.75

Table 6. Absolute Complexity Ratings, Sorted In Descending Order

The second questionnaire asked each Air Traffic Specialist to rate the different *combinations* of pairs of factors in the same manner as above. In this case, they were to assign a rating of "10" to a pair of factors that they feel, when combined, greatly impact the complexity of air traffic control, assign a rating of "1" to a pair of factors that they feel have very little impact on the complexity, and a rating of "5" to a pair of factors that they feel only somewhat impact the overall complexity of a situation.

Again, due to the large amount of data collected from this rating questionnaire (171 ratings for each of 10 Air Traffic Specialists), the summarized data tables are presented in Appendix B. However, as an example of this data, the absolute complexity rating data from the number of crossing altitude profiles factor [CAP] combined with every other factor is presented below, in Table 7.

For the final questionnaire, the Air Traffic Specialists were asked to rate the *relative* contribution of each of the listed factors, against all others. For example, the factor that they feel has the greatest impact on the complexity of an air traffic situation (above all other listed factors) was to be given the rating of "1." The factor that has the second greatest impact on the complexity (above all other remaining factors) was to be given the rating of "2," etc. For the relative rankings of the individual complexity factors, presented below sorted by Z scores, the weather data remains in the table due to the fact that if weather was not considered in the original rankings, the relative relationships between the other factors may have been different. The relative importance of weather, as shown in Table 8, however, will not be discussed.

	Absolute	
Factor Pairs	μ	$\sigma^{(n-1)}$
CAP x INT	7.8	1.48
CAP x DNS	7.6	1.96
CAP x PRX	7.3	2.21
CAP x CoD	7.1	2.13
CAP x PRF	7	1.94
CAP x CPA	7	2.91
CAP x NBR	6.7	2.87
CAP x SEP	6.7	1.77
CAP x ANG	6.6	2.59
CAP x VAS	6.4	2.91
CAP x CRD	6.1	3.07
CAP x VDF	5.7	3.43
CAP x STR	5.6	2.37
CAP x FAC	5.3	3.16
CAP x WND	5.2	2.90
CAP x SUA	4.8	2.66

Table 7. Combined Rating Data For [CAP] With Other Complexity Factors

Relative	
Factor	z Score
WDN	1.14
WST	1.01
INT	0.64
DNS	0.57
CoD	0.46
CPA	0.41
CAP	0.23
PRX	0.16
ANG	0.12
CRD	-0.14
NBR	-0.18
SEP	-0.21
VDF	-0.28
STR	-0.37
PRF	-0.41
SUA	-0.60
FAC	-0.68
VAS	-0.75
WND	-1.12

Table 8. Relative Ratings Between All Individual Factors, Sorted by Z Score

Both the qualitative data and the rating and ranking data were collected in order to gain some insight as to the appropriate weightings that should be assigned to each factor in the complexity measure. As well, the ranking data allowed us to determine which factors were considered to be the most important with respect to air traffic control. It was not realistic to assume that the impact that two factors would have on complexity would simply be an additive effect, based on the individual factor ratings. Therefore, the combinations of factors enabled us to examine if and how the weightings might change when two factors are combined.

The Factor Interviews provided additional detailed information about each factor, and the data from these interviews was used to support the numerical data with respect to how and when the weightings should be assigned. As well, the interview data was useful in understanding how participants might answer a question (i.e., how does factor "x" impact complexity) differently, based on the context in which that question was posed. The results from the data analysis and how these various sources of information were used in computing the actual complexity measure are presented next.

4.2.5 Controller-In-The-Loop Simulations

The major portion of our complexity measure development took place during Controller-in-the-loop simulations. Results from these simulations were used to modify the complexity algorithm, as necessary. For the simulation sessions, there were three different conditions under which our complexity measure would be validated. These conditions are referred to as (C)urrent, (H)alf Free Flight, and (F)ull Free Flight, and are explained below.

4.2.5.1 Conditions

(C)urrent Procedures. In an attempt to simulate current ATC procedures, Controller subjects were presented with aircraft flying on preferred routes, and were given full flight strips for all aircraft. Figure 8 below depicts a current procedures scenario (note the intersect points at which aircraft turn to follow another route) as it appears when viewed through our visualization tool. In addition to having aircraft on designated flight routes and providing the controller with full flight strip information, aircraft were required to request ATC clearances for any desired routing changes - as in today's system. For the scenarios presented under these conditions, actual SAR flight track data was not used primarily because the SAR data contains actual route changes initiated by Controllers when the data was collected.

Admittedly, even though the current air traffic situation in any given sector will have been influenced by previous control decisions, the instantaneous complexity experienced within a specific sector is, for the most part, wholly dependent on the decisions made within that sector. For example, if two traffic streams (one flowing South and one flowing West) cross within a sector (Sector C), the Controller working Sector C will be responsible for resolving any crossing conflicts that may occur in that sector (see Figure 9). The Controllers immediately North (Sector A) and East (Sector B) of Sector C will be resolving conflicts within their own sectors and will be maintaining separation within the traffic streams in their respective sectors. However, the Controller in Sector A will not be separating his/her aircraft based on the traffic streams in Sector B.

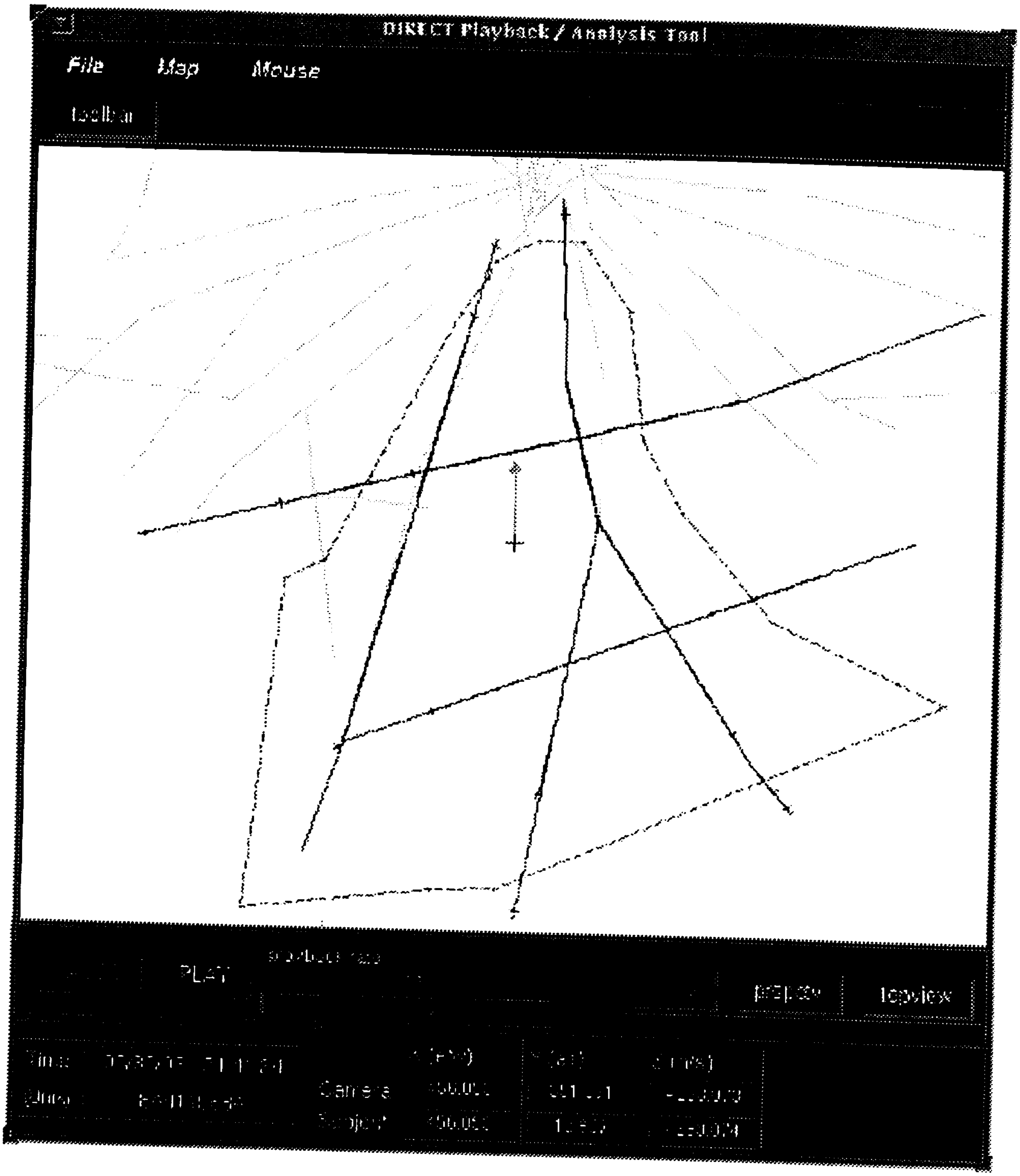

Figure 8. Current Procedures Scenario Viewed Through UI Tool

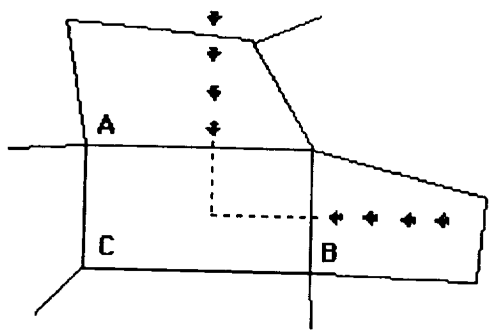

Figure 9. Responsibility For Conflict Resolution Within a Given Sector

(H)alf Free Flight Procedures. During the complexity focus group interviews, the discussions about aircraft intent information were very interesting. Every Controller felt that if s/he did not have aircraft intent information (with respect to changes in speeds, altitudes, headings, etc.) then the complexity would become very high. In one Controller's opinion, control would become "infinitely harder." In general, it is believed that Controllers may have a difficult time imagining a situation wherein they would not have short-term (i.e., 10 - 15 minutes) aircraft intent information, except, perhaps, for emergency conditions.

Therefore, to simulate the "Half Free Flight" portion of the simulations, we affected the short-term intent knowledge of Controllers by allowing aircraft to vary their heading within a 20 mile (10 miles to each side of their "direct" flight plan) "corridor," and their altitude by 500 feet in either direction of their assigned altitude, without requiring clearance from the Controller. The aircraft were still required to ask for clearance for such actions as turbulence avoidance, which would most likely change their altitude by more than 500 feet.

To simulate this increased aircraft flexibility, an additional Pseudo-pilot was used to input these changes on a scripted, aircraft-by-aircraft basis. In allowing this increased aircraft flexibility, we believe that this significantly impacted the complexity of control based on the lack of short-term intent information, which is in accordance with the level of importance Controllers placed on the knowledge of intent with respect to the complexity of control.

In addition, Controllers were presented with slightly modified flight strips, intended again to affect the knowledge of intent of each aircraft. Since aircraft were presented as flying along direct flight routes, Controllers were presented with departure and arrival airport identifiers. As well, Controllers were given the assigned altitude and current speed for each aircraft being controlled.

(F)ull Free Flight. The Half Free Flight condition was designed so that Controllers still had a certain level of knowledge of aircraft intent and were still responsible to maintain a certain level of control over aircraft routing. The Full Free Flight condition still presented Controllers with aircraft flying along direct flight routes, but in this case, the aircraft were allowed to change heading and/or altitude as desired, without necessarily requiring clearance from the Controller. Therefore, an additional Pseudo-pilot was again used to input "pilot-desired" aircraft routing changes on a scripted, aircraft-by-aircraft basis. However. as per the definition of free flight in the RTCA white paper, Controllers were still responsible for separation under certain conditions: (1) tactical conflict resolutions, (2) flow management, (3) resolution of unauthorized special use airspace (SUA) entry, and (4) flight safety violations (RTCA, 1995). In the event that a Controller needed to intervene, s/he communicated with the primary Pseudo-pilot and this pilot made the appropriate change in the aircraft route. For this condition, the only intent information given to Controllers was the origin and destination airports, which were presented on flight strips.

4.2.5.2 Scenarios

A total of thirteen (13) test scenarios were generated for use in the simulations. Four (4) scenarios were presented under the (C)urrent Procedures condition, six (6) under the (H)alf Free Flight condition, and three (3) under the (F)ull Free Flight condition. In addition, each scenario had one of three different levels of complexity, as computed by our algorithm. Each Controller was presented with two (2) Current Procedure scenarios, two (2) Half Free Flight scenarios, and one (1) Full Free Flight scenario. The order of the scenario presentation, as well as the level of scenario complexity, was randomized across Controllers. Scenarios were first generated by replaying recorded SAR data through a Complexity Analysis Tool (CAT), developed by Wyndemere. The CAT tool enables us to view various traffic scenarios, along with a computation of the complexity of that scenario, to identify specific situations which can be used for simulation purposes. These situations were then modified, using a software tool, to ensure that specific complexity factors were being experienced in order to validate our model appropriately. Originally, we wanted to analyze Official Airline Guide (OAG) data to identify specific situations of varying complexity to evaluate during our simulations. Unfortunately, the necessary OAG data was not made available to us in time for the simulations, so recorded SAR data was our best available alternative.

The following table shows the test matrix used for the validation simulations. Again, for this table, C represents those scenarios presented under Current Procedures, H represents Half Free Flight procedures, and F represents Full Free Flight procedures. The number (1, 3, 4, and 6 for conditions C; 1 -6 for H conditions; and 1 - 3 for F conditions) represents the number of the scenario (within each condition) presented to the Controller.

	Day 1	*Day 2*	*Day 3*	*Day 4*	*Day 5*
	C1	F1	C6	F2	C1
Morning	H2	H3	H3	C3	H4
Sessions		C6	F3	H1	C6
		H6	C1	H4	H1
		C4	H5	C6	F1
	H4	H5	C3	H6	H5
Afternoon	F3	H4	F1	C1	C4
Sessions		C1	C4	F3	F2
		F2	H6	H2	C3
		C3	H2	C4	H3

Table 9. Simulation Test Matrix

Scenario complexity was divided into three (3) levels: Low, moderate, and high complexity. For the Current and Half Free Flight Procedure conditions, C1 and H1 were rated low in complexity (based on our complexity algorithm); C3, H2 and H3 were rated to be of moderate complexity; and C4, C6, H4, H5, and H6 were rated to be of high complexity. For the Full Free Flight condition, scenario F1 was rated to be of moderate complexity, and scenarios F2 and F3 were rated to be of high complexity.

4.2.5.3 Sessions

The simulation sessions lasted a total of five days, with two Air Traffic Specialists participating per day. The first day served as a practice day to ensure system operation and to verify positive Controller response to the simulation environment. The ten (10) Air Traffic Specialists participating in the simulations were the same that participated in the Complexity Focus Group Interviews. For these simulations, verbal protocol data was not collected during the simulation. At times, problems such as intrusiveness or omissions may be encountered when collecting verbal protocol data. When performing complex tasks, operators typically do not speak aloud to explain each thought they may have, and doing so may prove difficult to do correctly. Thus, the protocol data is often collected after the completion of the experiment. In addition, verbal protocol analysis is not useful as a finite, answer-everything approach, but it can be used in conjunction with performance data to illustrate certain points, and it may be helpful in understanding subjects' strategies for performance (Sanderson et al, 1989). Therefore, to minimize the intrusiveness of data collection, the collection of this data was reserved for the debriefing session following each scenario.

For each scenario, one Air Traffic Specialist controlled the simulation (Radar Controller) while the other simply assumed a monitoring role (Radar Monitor). Communications between the Radar Controller and the Pseudo-Pilot occurred over the local office phone network, using headsets to simulate actual Controller headsets. The Radar Monitor did not have communications access with the Pseudo-Pilot. For the Half Free Flight and Full Free Flight scenarios an additional Pseudo-Pilot, who was not in communication with either the Radar Controller or the Radar Monitor, added inputs to select aircraft (based on a pre-written script) to simulate increased Pilot flexibility. The primary Pseudo-Pilot had full knowledge of these additional inputs so that he was able to communicate information about these flight path changes to the Controller, if necessary.

At the beginning of each morning and afternoon session, the Controllers were presented with a Half Free Flight calibration scenario. This scenario was rated to be of medium complexity. This calibration scenario was intended to familiarize the Controllers with the specific sector design to be used throughout the simulation, and to give them some familiarity with the concept of free flight and the fact that aircraft were able to change flight paths without acquiring Controller clearance. After the calibration scenario was completed, the Controllers were given a short break and then proceeded to control the test scenarios.

Before each test scenario, Controllers were presented with the flight strips for each aircraft in the scenario and were allowed time to evaluate the static traffic picture before assuming control. This static traffic picture was combined with a quick position briefing, given by a Wyndemere researcher, highlighting arrival aircraft and other specifics about the test scenario. After this position briefing, the dynamic simulation was started.

After each test scenario, the participants (both the Radar Controller and the Radar Monitor) were asked to evaluate the complexity of the traffic scenario using an established rating scale. This rating scale asked specific questions about the contributions of each factor to the complexity of the scenario, as well as an indication of the overall perceived complexity. We then compared these ratings with the complexity measure calculated by our model, to determine whether or not our model accurately represented a Controller's perception of air traffic complexity. Following this, a short discussion session was held to talk about the match (or mismatch) of the Controller ratings with this algorithmic computation. These discussion sessions were audiotaped and will be used for reference purposes when refining our complexity measure computation. Audiotaping these discussions allowed for a more natural conversational atmosphere than would have been experienced if one or more of the researchers had been required to take detailed notes during the conversations.

In addition to the Controllers' rating of the scenario, various simulation data items were recorded. This data included the flight paths followed by each aircraft and the commands given by the

Controller subject to the Pilots. This data was analyzed to determine if any operational errors occurred during the simulation, and to determine the level of efficiency of the flights in the scenario. Lower levels of efficiency may be an indication that the Controller was too busy to provide a more efficient flight, thereby providing an indication that the particular scenario was overly complex. Similarly, operational errors may be considered as indications that the Controller was again too busy with other tasks to notice a conflict or to resolve a conflict in a timely manner. Note that these 'other tasks' include all the tasks involved in the air traffic control process, not necessarily just the cognitive tasks. Finally, the measurement of the number of commands that the Radar Controller issued to aircraft during the test case was used as a measurement of the Controller's physical workload during the simulation test case.

After the first Radar Controller completed all 5 test scenarios, the two Controllers switched positions for the afternoon sessions. The scenarios presented to the second Radar Controller were different than the scenarios presented to the first Radar Controller in the morning sessions, because the second Controller had already seen the morning session scenarios while acting as a Radar Monitor. As in the morning sessions, the second Radar Controller completed the two calibration sessions, and was then presented with 5 test scenarios to control. Again, debriefing sessions were held after each scenario was completed.

4.2.5.4 Simulation Results

Results from the validation simulations were used to provide us with further insight into Controllers' perception of air traffic complexity. The two major sources of data collected were Controller ratings of scenario complexity and time-stamped logs of Pilot inputs (which serve as an indication of the number of Controller-issued commands). Audio recordings from scenario debriefings were also collected, to help us better understand the Controller-assigned complexity ratings. Although these sources of data were combined to give us a better overall understanding of air traffic complexity, the findings based on each data source will be discussed separately below.

Controller Complexity Ratings. Controller ratings of scenario complexity were collected after each scenario using a paper-based, numerical rating scale. The rating scale asked specific questions about the contributions of each factor to the complexity of the scenario, as well as an indication of the overall perceived complexity. Each rating scale ranged from "0" (no complexity) to "10".

To correctly compare Controller rankings, we needed to calibrate the Controllers' individual rating scales. For example, if one Controller feels that a "no complexity" scenario is any scenario with less than 10 aircraft then s/he would assign a 9-aircraft scenario a rating of "0." However, another Controller may feel that, theoretically, the only time a "0" rating should truly be assigned is when there are no aircraft to control. Therefore, this second Controller may assign the same 9-aircraft scenario a rating of "3." For illustrative purposes, assume that the "3" rating is the lowest rating the second Controller assigns to *any* scenario. Although both Controllers assigned the exact same scenario different ratings, in both cases the assigned rating was the lowest rating across all scenarios, per each Controller. Therefore, in order to account for this discrepancy in between-Controller ratings, the complexity rating results were normalized for each Controller (across all ratings assigned by each Controller) using the following equation:

$$SC_{new} = (SC_{old} - RANGE_{min}) \cdot \frac{6}{RANGE} + 3$$

Where *SC* represents each individual score assigned on the rating scale and *RANGE* represents the range of values (*MAX*. rating-*MIN*. rating) assigned by each Controller. The resulting transformation assigned a value of 3 to the lowest rating given by each Controller and a value of 9 to the highest rating. After transforming the rating scores, we computed a 95% confidence interval for each complexity factor rating, as well as for the overall complexity level, across all simulation conditions. The confidence intervals were then used as a target range of values against which to adjust our complexity measure.

<u>Time-Stamped Data Logs.</u> As part of our analysis of complexity, we evaluated the number of commands issued by Controllers under each level of complexity (see Figure 10, below).

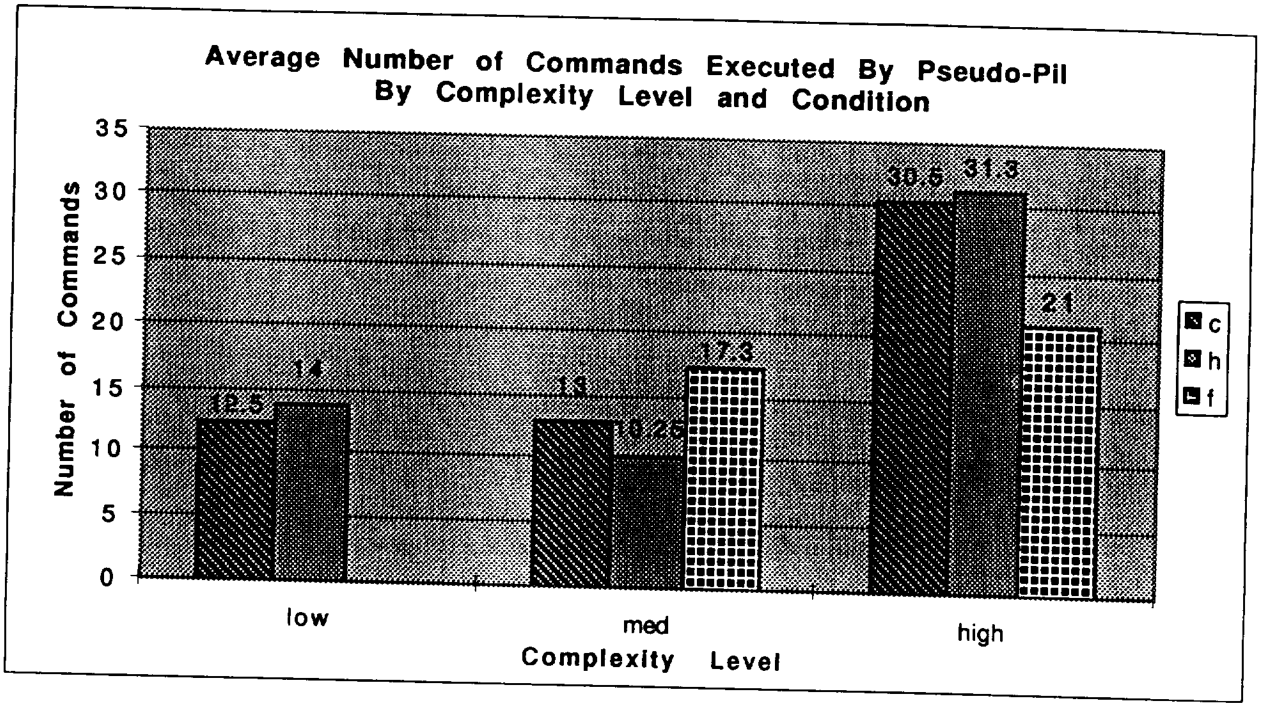

Figure 10. Number of Commands Issued For Each Complexity Level

According to Controllers, the complexity of control is partly based on the number of aircraft that are present in a sector. Furthermore, it is generally assumed to be true that as the number of aircraft increases, the number of clearances required also increases. The average number of aircraft presented under low, medium, and high complexity levels was 12, 12.75, and 17.86, respectively. Analysis of the number of commands issued under each complexity level indicates a significant increase in the number of commands issued under the highest level of complexity, as shown in Figure 10 ($F_{(2, 35)} = 20.07$; $p < .001$).

While this particular result is not necessarily surprising, we were intrigued by the relatively low number of clearances issued during high complexity, full free flight scenarios. Our original hypothesis was that there would be a significant increase in the number of commands issued under free flight conditions, regardless of complexity level. The data we had collected, however, did not indicate that this was true (see Figure 11 below).

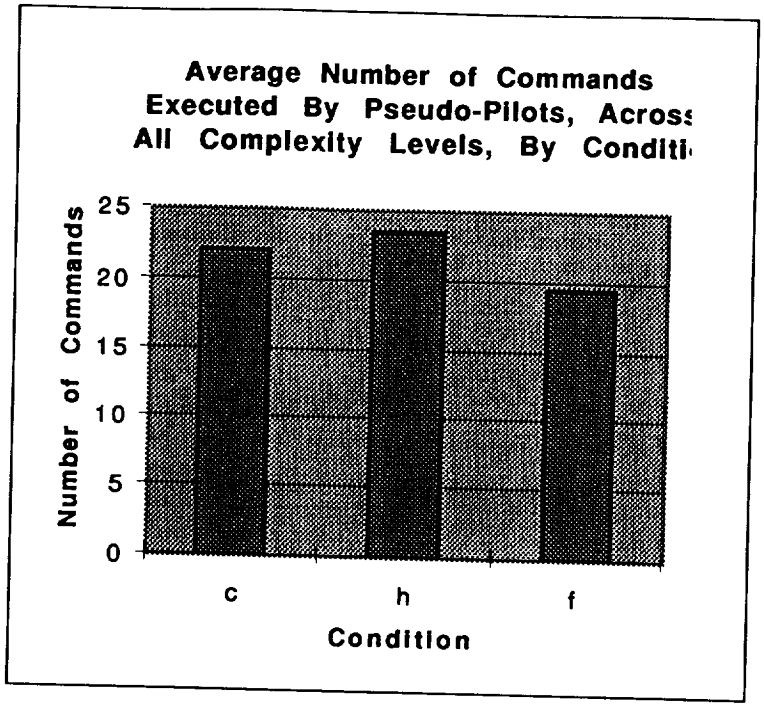

Figure 11. Number of Commands Issued in Current vs. Free Flight Conditions

Although the recorded data shows no significant increase in the number of commands given for the half- and full free flight conditions, observations made during the simulations suggest that Controllers did in fact issue more commands during free flight conditions. After examining our simulation procedures, we believe that the reason that the recorded data does not indicate this trend is the fact that PAS only logs commands that are actively input into the system by the Pseudo-pilots. Since the concept of free flight is still relatively undefined (from a procedural perspective), the procedures used by Controllers, and the clearances required to control traffic, were not defined for our simulations. Consequently, these procedures and clearances changed as the simulations proceeded. Throughout the free flight scenarios, Controllers generally allowed as many aircraft as possible to remain "in free flight." However, in certain cases, a Controller would need to ensure that two aircraft were going to remain separated by altitude and would therefore issue a short-term altitude restriction. If this restriction did not require the Pseudo-pilot to input a command, the clearance was not logged for data collection purposes.

For example, AAL1265 (currently flying at FL310) and UAL916 (FL290) are flying Heading 090 and 270, respectively. If AAL1265 were to descend or if UAL916 were to ascend, separation standards (which currently require 2000 feet of vertical separation between aircraft above FL290) would be violated. In order to ensure compliance with separation standards, and to ensure safety, the Controller might issue two commands such as, "AAL1265 *maintain at or above* FL310" and "UAL916 *maintain at or below* FL290." In this case, if the Pseudo-pilot does not have scripted altitude changes planned for the two aircraft in question, there is no danger of a conflict. Consequently, he or she will not input any system commands, and the Controller clearances will not be recorded. In order to capture the clearances, the Pseudo-pilots would have to enter AAL1265 A310 and UAL916 A290 ("A" is the PAS code used to input altitude commands), even though those are the altitudes that the aircraft are currently flying. This example scenario occurred a number of times throughout our simulations.

Future studies regarding free flight, using a similar testing environment, will account for this problem by 1) having a better definition of the procedures to be used for free flight conditions, and 2) keeping a record of the observed clearances, to be compared with the time-stamped data logs. It is worthy to note, however, that the reason that the free flight procedures were not more precisely defined in the current study is due in part to the fact that studying the physical communication workload levels associated with free flight was not a primary goal of our study. Also, we felt that requiring Controllers to learn new procedures would have only confounded our measurement of the complexity of control.

4.2.5.5 Simulation Comments

One of the most frequently heard comments throughout the simulation sessions was the fact that the Controllers did not have to actually coordinate any actions with other Controllers (adjacent sectors) or facilities (other ARTCCs or the TRACON). Many Controllers stated that part of the complexity of air traffic control is the direct result of the fact that, even in the least complex scenarios, they must coordinate point-outs and hand-offs with another Controller. If this other Controller is experiencing a very high level of complexity in his/her sector, it may take a considerable amount of time to respond. In addition, this additional task increases the cognitive load on both Controllers. The time lags and mental resource requirements that exist in this communication/coordination "system" can significantly increase the complexity experienced by the first Controller.

The impact of weather on the complexity of control was also not evaluated. The omission of weather data was simply due to the fact that Wyndemere does not currently have access to usable (for ATC simulation purposes) weather data. In future simulations aimed at understanding ATC complexity, it will be important to incorporate both the communication and coordination aspects of control and the impact that weather has on the complexity of controlling a specific air traffic situation.

5.1 ATC Complexity Measurement Environment (ACME)

The previous sections have described the process that was used to analyze the factors that contribute to ATC complexity. A major part of this research effort was the development of a Complexity Measurement tool that encodes the results of this analysis in computer software.

The approach that was used in the development of the Complexity Measure has been designed to allow the use of the measure in both a post-processing mode, as well as in an on-line, real-time mode. Basic air traffic control data is received by the ATC Complexity Measure Environment (ACME) system, and then analyzed to derive additional characteristics and predictions for individual flights. Once the complete set of flight characteristics are available for individual flights, flight segments are associated with specific airspace sectors. Finally, the traffic situation in each airspace sector is analyzed, and traffic characteristics of the overall traffic situation are evaluated. The Complexity Measure is then derived from these overall traffic situation characteristics. This process will be described in greater detail in the following paragraphs.

The ACME system operates in one of three different modes. These modes are intended to represent different ATC procedures that may exist in the next two decades of air transportation. The modes are Current Procedures, Half Free Flight and Full Free Flight. These exact definitions of these procedures have been described in Section 4.2.5.1, so only the use of these modes within the ACME system itself will be described here.

5.1.1 Flight Path Modeling

The basic data that is available from the primary ATC radar processing and display computer is Flight Plan and Track information. The ACME system assumes that Flight Plan information will be received from the primary ATC computer system for every aircraft that will be flying through a controlled region of airspace, although this is not completely true under the current system. Aircraft that are flying under Visual Flight Rules (VFR) can fly in airspace that is allocated to a Controller's sector without having a Flight Plan, and without being tracked by the primary ATC computer system. Such aircraft are not given clearances to provide separation. However, aircraft flying under VFR in a Controller's sector still add complexity to the air traffic situation in that the Controller is required to provide traffic advisories to aircraft that are being controlled in his or her sector airspace if the VFR aircraft may become a factor for the controlled aircraft.

The ACME system uses the Flight Plan information to predict the route of flight that the aircraft will follow. In all cases, the route of flight is predicted from the current position of the aircraft, through its full route of flight to touchdown at the aircraft's destination. The information that is used from the Flight Plan for this purpose includes the destination, route, aircraft type, and filed altitude. In the ACME Current Procedures mode, ATC Preferred Routes are assigned to each aircraft. During the Free Flight modes of operation, the ACME system generates direct routes of flight from the aircraft's current position to the destination.

For the first year of this study of ATC Complexity, the flight path modeling was only developed to a level of detail required to support the analyses of local ATC complexity. The flight path modeling system does not include avoidance of Special Use Airspace (SUA), nor does it include the generation of wind-optimized routes. Both of these improvements in the flight path modeling system would have increased the accuracy of the prediction of the characteristics of the complete flight. For example, the difference between departure to destination flight times between Current Procedures and Free Flight would be much more accurately estimated if the flight path modeling system included avoidance of SUAs and the use of wind-optimized routes. However, the intent of this study was to analyze the components of complexity in an ATC sector. Therefore, only local traffic characteristics need to be accurately modeled. While avoidance of SUAs and the use of wind-optimized routes would change the aircraft routes that are modeled, the change in local traffic characteristics within an ATC sector would be minimal. Since there are many other systems that already exist with very accurate flight path modeling systems, such as CTAS, it was not deemed useful to expend significant effort in the development of another system with highly accurate flight path modeling.

5.1.2 Trajectory Synthesis

At the initiation of work on the ACME system, an effort was made to utilize the Trajectory Synthesis (TS) module from the Center/TRACON Automation System (CTAS). The first effort undertaken was to integrate the TS from the Build 1 CTAS system, because the TS had been converted into a library with a simple function call interface. However, it was found that this version of the TS had not been sufficiently developed and tested to handle the complexity of flight routes that the ACME system required. At the point that this was discovered, a brief effort was undertaken to use the TS module from NASA's most recently released version of CTAS. However, it was decided that the increased effort required to interface with this TS was not in the best interest of the completion of the work outlined in the Statement of Work for this study.

Thus, a greatly simplified Trajectory Synthesis module was developed for this study. The TS utilized in the ACME system does not require the highly accurate thrust/drag modeling provided by the CTAS TS module, because the flight characteristics that are used for the Complexity Measure does not require modeling of aircraft turns or extremely accurate models of aircraft climbs and descents.

The TS module that has been developed for the ACME system is based on nominal speeds and rates for climb and descent, and the filed true airspeed for cruise computations. This approach greatly simplifies the TS, reduces the development effort required, significantly reduces the risk of software failure, and still provides the necessary accuracy for the purposes of this study.

Once the ACME system has generated the route of flight for an individual aircraft, a full trajectory is generated using the ACME TS module. The same set of input/output software structures in the CTAS TS module have been maintained in the ACME TS module. This will allow the CTAS module to be substituted into the ACME system at a later date, if desired. This also allows many of the CTAS utility routines for trajectory processing to be used in the ACME system.

5.1.3 Complexity Analysis Tool (CAT)

The computed trajectories for individual flights are sent to an ACME System module called the Complexity Analysis Tool (CAT). The CAT module utilizes the trajectory utility routines to generate predicted track points at 10 second intervals. Each of these track points is then analyzed to determine which sector the aircraft will be in at the prediction time.

The ACME system uses an adaptation file that specifies the regions of airspace that make up ATC sectors. These ATC sectors are defined by one or more altitude ranges associated with an enclosed polygon. The data that specifies these airspace sectors is obtained from the Adaptation Controlled Environment System (ACES) data that is used at ARTCC ATC facilities.

The Complexity Measure is composed of a number of individual complexity components that are factors in the overall measure of complexity. These complexity components are computed within the CAT module by evaluating characteristics of individual flights, and then computing the aggregate effect of the individual characteristics on the overall traffic situation in the sector.

Each complexity component is evaluated at an instant in time based on the current or predicted aircraft state for that instant in time. The 10 second track points are used as the aircraft state for the evaluation time. For example, one of the complexity components is a count of the number of aircraft that are either climbing or descending in the sector (CoD). The CAT module computes this complexity component starting at the current time and looking forward into the future by a time parameter that can be varied by the user. The complexity components are calculated at time intervals into the future that are set by a parameter. For example, the complexity components may be computed every minute for 120 minutes. This gives a two hour look-ahead for complexity information. For the complexity component that measures the number of climbing or descending aircraft, the CAT module searches the list of track points for each aircraft for each complexity computation time interval and checks to see if the track point is within one of the sectors for which complexity is measured. If the track point is within the sector, and that track point is in a climbing or descending flight segment, then the CoD complexity component will be increased by one unit for that time period in that sector.

However, the Air Traffic Controller is constantly predicting situations that may occur in the future, and formulating a plan to deal with such situations. Thus, it is often future events that affect the overall complexity of the situation for the Controller at an instant in time. For example, if an aircraft is going to descend from cruise to approach its destination airport, the Controller must look forward in time and predict the possible interactions between the descending aircraft and other aircraft that the Controller is responsible for, or will be responsible for, in the future. The Controller's complexity is affected at the current time by events that will occur in the future, in this case, a descending aircraft.

The formulation used for the DIRECT Complexity Measure is to measure the individual complexity components at an instant in time. Then, the effect of a given complexity measure on the overall complexity at time $t(n)$ will be a function of the component complexity at time $t(n)$ through $t(n+m)$. Here, m is the look-ahead time for that particular component complexity measure.

5.1.4 Individual Complexity Measures

The following paragraphs will describe the different complexity components that are computed by the ACME system and used in the Complexity Measure. Following the description of the complexity components, the methods that are used to formulate the overall complexity measure from the component complexities will be described. All of these activities are performed in the CAT module.

The first step in computing the complexity algorithm was to examine the complexity factors, individually, to determine whether it was feasible to include each factor in the algorithm. Ideally, we would have liked to include every factor identified in the Focus Group Sessions in our complexity algorithm. However, for some of the factors (CRD, FAC, SEP, and WND), we do not have sufficient data or resources and would therefore not be able to properly validate these measures during our simulations.

The reason CRD and FAC were not used in our algorithm is primarily due to our limited simulation capabilities. The impact that coordination has on the complexity of control can only be truly investigated with a relatively large number of Controllers and Pseudo-pilots. The intricacies of the coordination that Controllers must perform with other Controllers (either within their own ARTCC or in other ARTCC facilities) can only be captured if there are a number of other people available to fill these additional roles. The impact of separation requirements (SEP) on complexity was considered in this study is because we wanted to focus our study on the elements of the traffic situation that impact the complexity of control. Separation requirements (i.e., miles-in-trail) are imposed by an Air Traffic Control facility and are therefore not considered to be elements of the traffic situation itself. Since our system capabilities do not allow us to simulate flow control decisions, the investigation of the impact that SEP has on the complexity of control could not be properly simulated.

Finally, wind and weather information is not available for simulation at this time. Therefore we could not examine the impact that WND, WDN, or WST has on the complexity of control. For the simulation purposes, we assumed zero-wind, clear weather conditions across all scenarios.

Based on the data collected throughout the study, the individual complexity factors, along with a description of how they were initially computed, are presented below:

5.1.4.1 Aircraft Count (ACT)

This complexity component is simply a count of the number of aircraft within the lateral and altitude boundaries of the sector at an instant in time. The Aircraft Count component of complexity is used to provide an indication of the number of clearances that will be required of a Controller, and the number of individual aircraft entities that the Controller has to mentally monitor and track.

5.1.4.2 Convergence Angle (ANG)

This complexity component is a measurement of the severity of each conflict situation based on the conflict geometry. The data used to create the computation method for this complexity component was also obtained through the Focus Group Sessions. Different conflict geometries were evaluated with the Controllers to determine the relative complexity of conflict geometries. The results indicated that conflicts with a small convergence angle between the aircraft are the most complex conflicts to handle. Head-on conflicts are also high on a relative complexity scale of conflict geometry, while 90 degree intercept conflicts are considered to be the easiest to deal with.

The Convergence Angle complexity component quantifies the interview results through a functional relationship between intercept angle within a conflict, and the component score. A score of one unit is assigned to a conflict with an intercept angle of zero degrees. As the convergence angle increases to 90 degrees, the component score decreases. The score then again increases with convergence angle back to one full unit for a head-on convergence angle.

5.1.4.3 Crossing Altitude Profiles (CAP)

This complexity component is a count of the number of pairs of aircraft in which one aircraft will be climbing and one aircraft will be descending through the same altitude. This complexity component models situations in which the Controller has to ensure lateral separation, and can't rely on altitude.

5.1.4.4 Climbing or Descending Aircraft (CoD)

This component is a count of the number of aircraft that are in climb or descent at an instant in time. When an aircraft is climbing or descending, the traffic situations at different altitude levels are no longer separable for the Controller. The complexity of the situation that the Controller has to address is increased through the interactions of flights as altitude levels are changing.

5.1.4.5 Closest Points of Approach (CPA)

This complexity measure is a weighting of the number of aircraft that are within a threshold separation of each other at any instant in time. Note again that this instant in time may be a predicted instant. Thus, this complexity component is predicting potential losses of separation. However, the complexity component itself is only non-zero at a time, n, at which the aircraft states are actually predicted to be within a given threshold, rather than being non-zero if there is a predicted conflict some time after time n.

The threshold values used in these closest approach analyses are 8 miles and 13 miles. These threshold values were the result of the Complexity Focus Group Sessions. The 8 mile threshold is used as an indication of a predicted separation that would cause action on the part of the Controller. In the computation of the complexity measure, one unit is added to the CAP component at any time at which two aircraft are predicted to be within 8 miles of each other. The 13 mile threshold is used as an indication of a predicted separation that would cause heightened separation monitoring between the two aircraft by the Controller. One half unit is added to the CAP component at any time at which two aircraft are predicted to be more than 8 miles apart, but less than 13.

5.1.4.6 Aircraft Density (DNS)

Aircraft Density is the aircraft count divided by the usable amount of sector airspace. This complexity component is used to model the general conflict potential between aircraft, based on the amount of airspace that is available on a per aircraft basis. This component also provides correlation with the flexibility that a Controller has with each aircraft in his or her sector, again due to the amount of airspace that is available on a per aircraft basis.

5.1.4.7 Intent Knowledge (INT)

The level of information about the intent of the aircraft is also evaluated. This measure is somewhat simplistic at the current time, being classified into three levels of intent knowledge - current procedures, half free flight and full free flight. The complexity for each aircraft associated with intent knowledge of current procedures is zero, full free flight is one, and half free flight is one-half. The half free flight case assumes an interim implementation of free flight in which destination, altitude, and airspeed information is known through a flight plan, and the deviations from those parameters is limited. Again, a more complete description of these levels can be found in Section 4.4.2, Validation Simulations.

5.1.4.8 Aircraft Neighboring Conflict (NBR)

For each instant in which two or more aircraft are predicted to be within a threshold separation, a count is made of other aircraft that are within the general area of the potential conflict. This component is used to model the reduction in flexibility that a Controller has in order to resolve a conflict when specific aircraft are within the region of the conflict. The computation of this complexity measure scores one unit for each aircraft that is within 10 lateral miles and 2000 vertical feet of a conflict location.

5.1.4.9 Conflict Near Sector Boundary (PRX-C)

This complexity component is a count of the predicted conflicts that will occur within a threshold distance of a sector boundary. This complexity component is used to model the fact that a Controller may have less time to resolve a conflict situation that is near a sector boundary, because control of one or both of the aircraft may only be transferred to the receiving Controller shortly before the conflict is to occur. This component is also used to model the fact that the Controller's complexity may be increased by having to coordinate with adjacent sectors to complete the resolution of the conflict. The computation of this complexity component scores one unit for each conflict that is within 10 miles of the sector boundary, and one half unit for each conflict that is within 20 miles of the sector boundary.

5.1.4.10 Altitude Variation (VAA)

This component is a measure of the variability of altitude of all of the aircraft in the sector at any instant. This complexity component is computed by the ACME system, but there is no evidence from the Controller interviews that altitude variation itself has any impact on Controller complexity.

5.1.4.11 Heading Variation (VDF)

This component is a measure of the variability of heading of all of the aircraft in the sector at a time instant. A higher heading variability of the traffic situation provides less organization of the traffic flow for the Controller. With lower heading variability, often the Controller can group individual aircraft together as traveling in the same basic direction across his or her sector. In this manner, a mental dependency between two aircraft that provides a quick check for separation can be created. This simplifies the situation for the Controller.

Since heading is a cyclic parameter (0 to 360 is the same as 360 to 720), the variation is computed through the use of a pair-wise minimum heading difference squared and summed over all aircraft pairs. Consider, for example, the standard variation calculation for one aircraft heading 359 degrees and a second aircraft heading 001 degrees. A standard calculation of the variation of this data set would use an average of 180, and square and sum the differences between the headings of the aircraft and the average heading of 180. However, a heading of 360 is a more correct average to use in this case.

In cases with more than two aircraft, the best average to use is not as readily apparent. The variation calculation used for this complexity component removes the use of an average value, and only uses differences between two headings. In this manner, the numerical ambiguity that results from the standard variation calculation is avoided:

$$\frac{1}{(n)\cdot(n+1)}\sum_i \sum_{j:j\neq i}\left(hdg_i - hdg_j\right)^2$$

5.1.4.12 Speed Mix (VAS)

This component is a measure of the variability of ground speed of all of the aircraft in the sector at a time instant. The variability of ground speed affects the complexity of the traffic situation for the Controller by causing potential overtake situations, and increasing the difficulty of predicting relative future positions of aircraft because of the differing ground speeds. Since ground speed is not a cyclic parameter, a standard variation calculation is used.

5.1.4.13 Aircraft Proximity to Sector Boundary (PRX)

This complexity component is a count of the aircraft that are within a threshold distance of a sector boundary at a given time instant. When aircraft are near a sector boundary, a greater amount of coordination and monitoring is required, which can increase Controller complexity.

5.1.4.14 Airspace Structure (STR)

This complexity component measures the conformance of the traffic flow through a sector to the geometry of the sector. In general, sectors are designed for specific air traffic flows. For example, arrival sectors are generally designed to be longer and narrower than normal sectors, and are oriented toward the arrival terminal area. A large percentage of the aircraft that fly through this sector are flying to the arrival terminal area, so the aircraft fly in the same general direction through the length of the sector.

A Controller's complexity can be increased if there are aircraft flying 'against the grain' of the sector. In other words, if aircraft are flying across the major flow of traffic and/or flying across the shorter width of the sector, the Controller must engage in additional conflict monitoring and/or coordination. The computation of this complexity component is performed by calculating a major axis and aspect ratio for the sector. Then, the difference in heading between each aircraft and the major axis is computed. The squared deviation from the major axis of the sector is weighted by the aspect ratio and then summed over all aircraft.

5.1.5 Factor Combinations

The next step in formulating our complexity algorithm was to determine how the individual factor weightings might be changed when combined with other factors. To begin this process, we first examined the absolute ratings given to each factor pair. We used this data to get a general understanding of the absolute level of complexity associated with two combined factors. Tables containing this data are presented in Appendix A, along with the Factor Interview data summaries.

The second step in determining the weightings based on factor combinations was to examine the difference between the absolute ratings given for each individual factor and the absolute ratings given to that factor combined with every other factor. Statistical t-tests were performed on each distribution (i.e., [CAP] vs. [CAP x STR], [CAP] vs. [CAP x SUA], etc.), assuming equal variances. For all statistically significant results (i.e., the two distributions were found to be significantly different), the t-test results are presented and discussed in Appendix A. In addition, possible reasons for why a significant difference was found, and the implications that the finding has on the measurement of complexity will be given. An example showing this process is presented below:

Single Factor Ratings

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	μ	$\sigma^{(n-1)}$
CAP	8	8	9	6	3	9	7	6	10	6	7.2	2.044

Factor Combination Ratings

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	μ	$\sigma^{(n-1)}$
CAP x STR	5	8	9	6	5	3	7	7	5	1	5.6	2.3664
CAP x SUA	3	6	9	2	5	4	9	4	5	1	4.8	2.6583
CAP x PRX	8	9	10	8	6	3	9	6	5	9	7.3	2.2136

In this example, statistical analyses revealed a significant difference between the absolute ratings assigned for [CAP] and the absolute ratings assigned for [CAP x SUA] ($t = 2.26$; $p < 0.037$, two-tailed). However, we see that the absolute rating of complexity associated with the combination of these two factors is significantly lower than the absolute rating of complexity assigned to the individual factor [CAP] alone. A possible reason for this might be explained by the fact that SUAs are usually not located in the direct path of a portion of airspace. If this should happen, however, the Controller might opt to have, for example, all climbing aircraft to go around the north side of the SUA, and all descending aircraft go around the south side of the SUA. Therefore, the complexity of that scenario would not be considered as great an impact on complexity as the presence of a large number of crossing altitude profiles between two aircraft.

An interesting problem is highlighted in this example. From an intuitive standpoint, we would expect to see an *increase* in absolute complexity, when a Controller has to deal with aircraft that have crossing altitude profiles [CAP] *and* has to route traffic around a Special Use Airspace [SUA] simply because of the fact that more aircraft route changes would most likely be required. The fact that there was a significant *decrease* in this rating leads us to believe that the participants may not have all been using the same decision criteria when assigning factor weightings. It became apparent to us that in comparing the quantitative, numerical data for the combined ratings with the qualitative, interview data, the Controllers may have inadvertently assigned a ranking based on an assumed (but unknown to us) relationship between those two factors.

This fact is further evidenced upon examination of a simple correlation matrix between individual factor, absolute ratings. In many cases, the correlations obtained do not provide any reliable correspondence to the combined factor ratings. Although no statistical tests were run to investigate this phenomenon, a cursory examination of the data does indicate that Controllers may have assumed the existence of additional relationships between factors when assigning the combined rankings. Thus, in identifying weightings for combined factors, we decided to use the more detailed--but difficult to quantify due to its variance and subjectivity--interview data as a basis for our assignments. We believe that through a careful examination of the interview data, we will be better able to capture the essence of the Controller-assigned weightings. Due to the nature of the interview data, we also realize that a certain level of researcher subjectivity will impact the assigned weightings. However, since this study is designed to allow us to further modify our weightings based on simulation results, we feel that this is still an acceptable step towards defining and measuring complexity.

5.1.6 Overall Complexity

The overall Complexity Measure is computed through a combination of these individual complexity measures. An additive formulation has been used for the combination of individual complexity measures into the overall Complexity Measure. There was some evidence over the course of the study that formulations other than additive may have been appropriate. However, in most of the cases that indicated a different form of combination of individual complexity measures would be more appropriate, there was a clear operational combination of factors. In these cases, it was often possible to create new individual complexity measures that were computed through more general combinations of other individual complexity measures. For example, the Airspace Structure (STR) complexity measure is actually a combination of sector shape and variability of direction of flight in a form other than additive.

Three different approaches are used to combine the effects of the individual complexity components into the overall Complexity Measure. These approaches are used to model the operational impact that each of the complexity components has on the overall complexity. The three approaches are referred to as Maximum, Cumulative, and Weighted, and are described below. A different mathematical function is used to compute the contribution to the overall complexity for each of these three approaches, and more than one of these approaches can be used for a single component of complexity. The results of the application of these mathematical functions to the individual complexity measures are then combined additively to form the overall Complexity Measure.

5.1.6.1 Maximum

Many of the individual complexity components model characteristics of the traffic scenario, while other complexity components model events within the traffic scenario. Characteristics of the traffic scenario persist through the full time span of the traffic scenario, whereas events have a specific time associated with them. The Maximum approach to computing the contribution of a complexity component to the overall complexity is intended to model the requirement of the Controller to handle a traffic characteristic with a specified look-ahead time. The Controller's complexity will be proportional to the maximum level of the complexity component over the look-ahead time. The look-ahead time models the range of time into the future over which the Controller is monitoring the specific complexity component.

If the component complexity is contributing to the overall complexity through a maximum function, the maximum value of the component complexity between time n and time $n+m$ is weighted by a factor W and added to the overall complexity measure:

$$O_i = W_i MAX(F_i(n), \ldots, F_i(n+m))$$

5.1.6.2 Cumulative

Other individual complexity components model events that are predicted to occur in the traffic scenario. Events that are predicted to occur in the traffic situation are generally dealt with for a limited period of time, with a specific set of clearances. Individual complexity measures that model events in the traffic situation will use the Cumulative function to sum all the effects of these events in the traffic situation. Since each of these events is solved through a specific set of clearances, the complexity of planning and conducting the resolution of these predicted events will sum independently.

$$O_i = W_i \sum_{n}^{N+m} F_i(k)$$

5.1.6.3 Weighted

Another approach is also available to combining the effects of predicted events into the overall Complexity Measure. This approach, the Weighted function, models the situation in which events that will occur sooner may cause more complexity than events that will occur later. This approach is similar to the Cumulative function, with the addition of a time-based weighting factor.

$$O_i = W_i \sum_{n}^{n+m} (n+m-k) \cdot F_i(k)$$

Verification and validation of the complexity measure, after the initial algorithm was completed and the weightings had been assigned, was the focus of collecting the data during the Controller-In-The-Loop simulations. This verification/validation process was very complicated due to the large number of factors that were included in the model and the complexities of the simulation test matrix itself. In summary, the validation methodology used was to use an initial complexity measure to generate a number of scenarios of varied levels of complexity, with each of these scenarios controlled in simulation by the same Air Traffic Specialists used in the Complexity Focus Group Sessions. The results from the simulations were used to refine and further develop the complexity measure. Below, we describe the iterative approach we took to developing the complexity measure.

5.2 Refining The Complexity Measure

5.2.1 Measurement Iterations

After the completion of the validation simulations, our next task was to refine the complexity algorithm to more closely represent the ratings controllers assigned during the simulations. Indeed, given the subjective nature of the data we were dealing with, it is not surprising that the process of formulating a mathematical model of controller perceptions is an iterative one. Prior to the simulations, each simulation session was run through the ACME system, resulting in a set of complexity values for each individual factor as well as the overall complexity. This complexity data was not shown to the controllers during the simulations. However, at the end of each simulation day, controllers were able to view the complexity measure results as part of their debriefing.

In general, the methodology used was to refine the ACME system so that it could accurately measure (according to Controller perceptions) the complexity of an air traffic situation on a factor-by-factor basis. Having done this, we then analyzed the Controller ratings from the simulation sessions to determine the relationship that exists between the ratings that Controllers assigned to the individual factors and the overall complexity ratings. In doing so, we are now able to individually analyze the impact that a specific complexity factor has on an air traffic situation as well as understand how that individual factor contributes to the overall complexity.

5.2.1.1 Individual Factors

The first step taken to refine the individual factor complexity measures was to plot the Controller ratings against the initial values computed by the original complexity algorithm, for each complexity factor. Each simulation scenario was run through the ACME system, resulting in a complexity value for each factor, for each scenario. These values were a mathematical representation of the information collected during the Focus Group Interviews, scaled to range from a value of 1 to 10. Plotting this information allowed us to see how our initial computations of factor complexity compared to the Controller ratings taken during the simulation sessions (see Appendix C).

Next, using a simple linear regression equation, we analyzed the Controller ratings versus the ACME system ratings to generate a new set of coefficients to be used for our complexity algorithm. The reason this iteration was conducted was to try to match, as closely as possible, the algorithm values with the Controller ratings. Again, the simulation scenarios were run through the ACME system (using the new coefficients) and the complexity values were recorded. These values were also plotted against Controller simulation ratings, allowing us to see how well our revised complexity algorithm was computing values that matched controller perceptions of the individual complexity factors only. An example results table (for the density [DNS] factor) from these individual factor analyses is shown below in Table 10. The corresponding data plot is shown in Figure 12. The data plots for each complexity factor is found in Appendix C.

Regression	Statistics
Multiple R	0.67244958
R Square	0.45218844
Adjusted R Square	0.36885511
Standard Error	1.13499843
Observations	13

	Coefficients	Standard Error	t Stat	P-value
Intercept	0	#N/A	#N/A	#N/A
CONTRIB	5.57890637	0.28336713	19.6879096	1.6758E-10

Table 10. Example Regression Result From Individual Factor Analyses

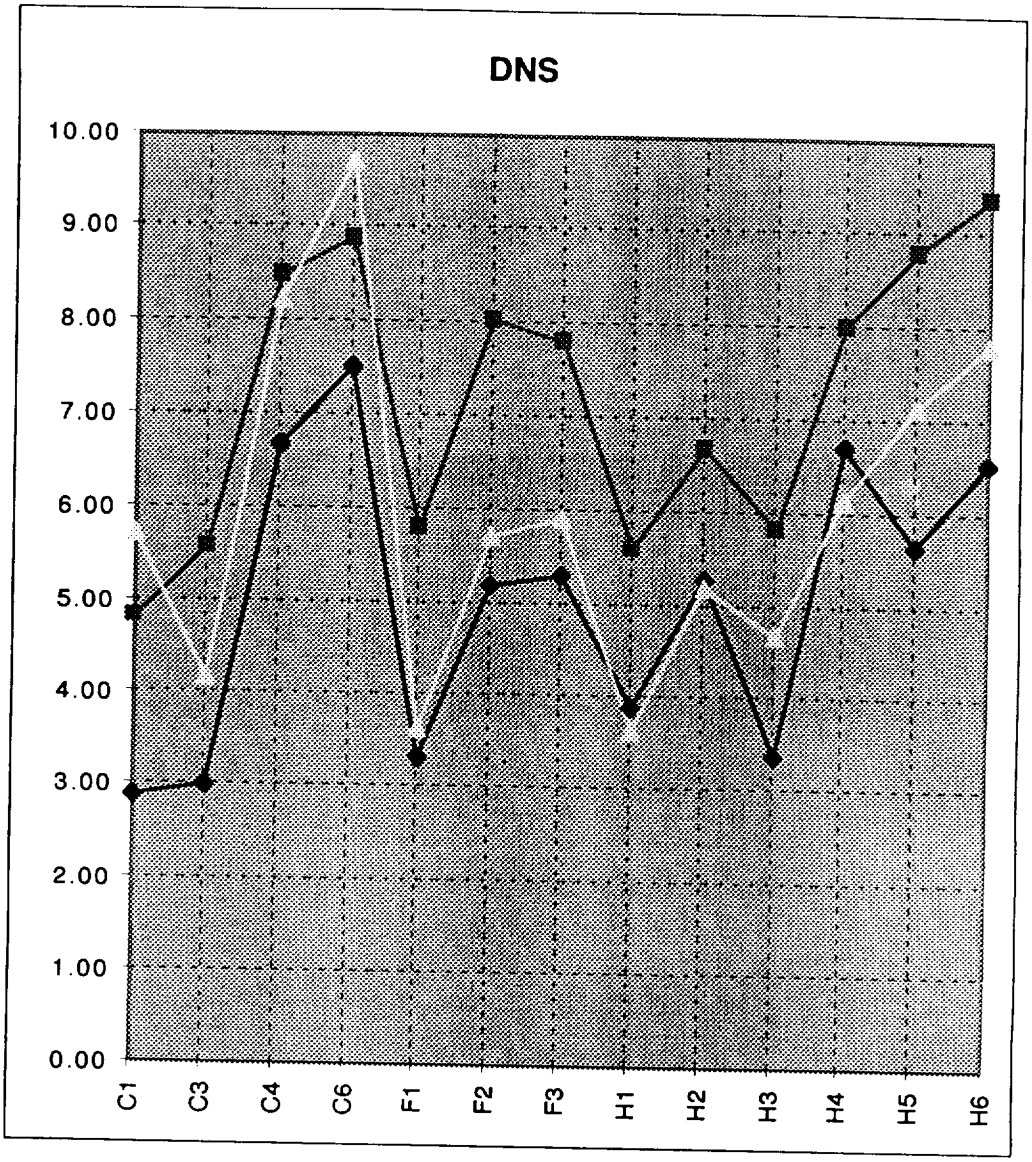

Figure 12. Example Data Plot From Individual Factor Analyses

While the exact values obtained from our complexity algorithm (on a factor by factor basis) may not *exactly* match Controller ratings, it is important to note that both the complexity algorithm computations and the Controller ratings tend to follow similar trends across conditions (C, H, or F) and complexity levels (low, medium, and high). This suggests that our complexity measure is capturing some aspect of the Controllers' perception of how complexities change in different traffic situations, on a factor-by-factor basis.

5.2.1.2 Overall Complexity

The next step in refining our complexity algorithm was to determine how the Controllers combine the effects of individual complexity factors into a rating of overall complexity. During the Focus Group Interviews, the Controllers found it very difficult to explicitly state the relationship that exists between individual factor complexities and the overall complexity of an air traffic situation.

Therefore, we used the simulation data to uncover this information by examining the relationship between Controller ratings of the individual complexity factors with their ratings of the overall complexity. The process for this analysis was to perform a multiple regression analysis across all Controller ratings and across all scenarios. This regression provided us with the weighting coefficients needed to combine our individual factor computations into an overall complexity measure to match Controllers' perceptions of overall scenario complexity.

This part of the analysis provided insight into the factors that are, mathematically, believed to play a significant role in the overall complexity of an air traffic situation. Since all of the individual factor weights were scaled to the same range (from 0 to 10) the coefficients determined through the multi-variable linear regression provide an indication of the relative significance of each of the individual complexity factors to the overall complexity. The resulting coefficients from this analysis were as follows:

Regression	Statistics
Multiple R	0.87668129
R Square	0.76857008
Adjusted R Square	0.7171827
Standard Error	1.06298846
Observations	81

Factor	Coefficient
Intercept	0
INT	0.05121707
DNS	0.46770975
ACT	0.02455453
CoD	0.16164556
NBR	0.06071066
CPA	0.07104819
ANG	0.15247093
PRX	-0.1406604
PRX-C	0.10745819
VAS	-0.0045182
VDF	0.10182903
STR	0.09646242

Table 11. Coefficients For Computing Relationship Between Individual Factors and Overall

Note that in the above coefficients two of the values (PRX and VAS) are negative. The negative coefficients imply that there is a negative relationship between those factors and the overall measure of complexity. For example, the negative coefficient for PRX implies that as the amount of complexity associated with aircraft which are near sector boundaries *decreases*, the overall complexity level *increases*. However, in an operational setting, we would expect to see a decrease in the overall complexity of a situation with a decrease in the complexity associated with PRX.

Therefore, the two factors with negative coefficients were dropped from the overall complexity measure for two main reasons. First, the information obtained during the Focus Group Sessions indicate that that there should in fact be a positive correlation between the PRX factor and the overall complexity measurement. What this suggests is that there are unknown relationships between other factors that we have not yet been able to account for.

Second, the amount of data we had available to perform the regression was most likely substantially lower than would be needed to get a statistically significant result. In fact, it was very difficult to assess the complexity ratings for each scenario across Controllers because each Controller only worked a subset of the total number of scenarios. Because we wanted to examine the Controllers' perceptions of complexity when placed in a monitoring role, it was necessary to ensure that the Air Traffic Specialists were not presented with the exact same traffic scenario when assuming the roles of both Radar Controller and Radar Monitor. In addition, the Controllers we used in this study were all full-time, active FPL Controllers. As such, they were not able to allocate the amount of time (at least 1 full day as a Radar Controller and 1 full day as a Radar Monitor) that would have been necessary to completely run all 13 scenarios.

After dropping the negative coefficients, the complexity measure was analyzed with recorded traffic operations to evaluate the realism of the complexity measure in actual traffic operations. Through these analyses, differences between the simulation scenarios that were used with the controller subjects, and actual traffic operations were observed. Many of these differences were also noted by the controller subjects. One of the primary differences is that the simulation scenarios were specifically developed to provide a single traffic situation for the simulation subject to address. However, actual traffic operations are more continuous, with aircraft entering and leaving the sector at much more diverse times. These differences resulted in the need to modify some of the factor contributions to the overall complexity. The final complexity measure is shown in figure 12, below. A comparison of the final complexity measure to the overall Controller ratings is shown in Figure 13.

0.0172 x ACT (MAX., 10.0)
0.328 x DNS (MAX., 10.0)
0.0498 x CPA (SUM, 15.0)
0.1070 x ANG (SUM, 15.0)
0.0426 x NBR (SUM, 15.0)
0.0754 x PRX-C (SUM, 15.0)
0.1134 x CoD (SUM, 15.0)
0.0709 x VDF (MAX., 10.0)
0.0 x VAS (MAX., 10.0)
0.2 x PRX (SUM, 10.0)
0.0676 x STR (MAX., 10.0)
\+ 0.2564 x INT (MAX., 10.0)

OVERALL COMPLEXITY

Figure 13. The Final Complexity Algorithm

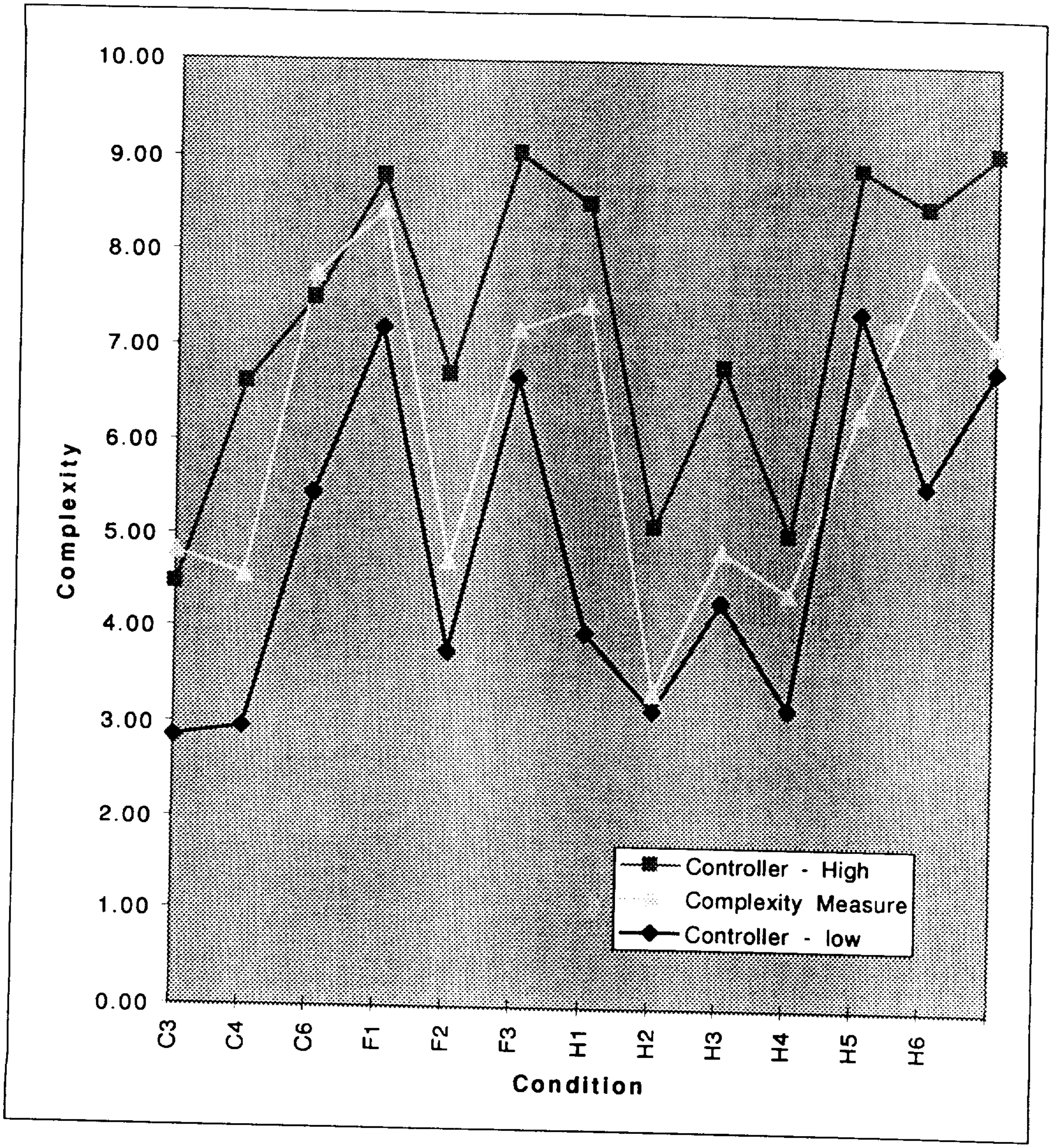

Figure 14. Final Overall Complexity Measure vs. Controller Ratings

6.1 Rationale

A major focus of this study has been the use of the complexity measure that has been generated and validated to conduct a comparison of similar traffic situations under current procedures and free flight procedures. Other studies have performed similar analyses of traffic under the free flight concept. However, these studies only considered changes in airspace density and conflict events. As has been found through the controller interviews and simulations that have been conducted as part of the current study, density and conflict events do play a major role in the overall complexity of the ATC situation, but these two factors do not determine the ATC complexity exclusively. There are many other characteristics of the ATC situation that will be significantly different under the identified free flight procedures. These characteristics must be considered in any analysis that compares the complexity of the ATC situation between clearance-based procedures and free flight. This study has attempted to consider all of the major characteristics of the traffic situation in a comparison of current procedures and Free Flight procedures, as will be described below.

6.1.1 Caveats of the Traffic Complexity Analysis

Note that our initial analysis of traffic situations was conducted with a fast-time simulation system that does not consider some of the important elements of a truly realistic traffic situation. For example, Special Use Airspace, dynamic winds, and hazardous weather are not considered in this study. Additionally, some components of the fast-time simulation system have not been developed to a level of accuracy that matches the current state-of-the-art. Examples in this category are the trajectory synthesis logic, and the adaptation data that specifies the ATC Preferred Routes that are used under current procedures. Initially, an attempt was made to use the trajectory synthesis module from CTAS, which would have been much more accurate. However, a number of bugs were noted in the CTAS Build 1 TS module, and the TS in the NASA baseline did not have a convenient software interface, due to the use of shared memory.

The ATC Preferred Route data that was used for the study was obtained from the FAA's National Flight Data Center (NFDC) data. A number of airspace data files are maintained by this group in the FAA. These airspace data files include data for Navaids, Fixes, Airways, Airports and Runways, SIDs and STARs, Special Use Airspace, ATC Preferred Routes, and others. The NFDC data file for the ATC Preferred Routes data makes reference to data contained in the Navaids, Fixes, Airways, Airports, and SIDs and STARs files. Unfortunately, it was found that these data files do not have consistency between themselves. The DIRECT research team made extensive efforts to force consistency into the data but this was not possible. In addition, contact was made with the organization of the FAA that maintains the NFDC data to determine if there was additional information that was not released with the NFDC data that would make it consistent. The NFDC group of the FAA stated that the NFDC data is not consistent, and in fact, little effort is currently made to ensure such consistency. The system that maintains the NFDC data is currently being upgraded by the FAA, and one of the major goals of this upgrade is to add consistency to the data.

Unfortunately, the NFDC data will not be consistent with itself until sometime in late 1997. A member of the DIRECT research team personally visited with the NFDC group of the FAA to receive a briefing on the status of the upgrade, and to determine if there was any means by which consistent data could be obtained at an earlier date. Unfortunately, this study has been forced to use the inconsistent data for the analysis. The primary result of this inconsistency is that many (more than 50%) of the ATC Preferred Routes in the NFDC data cannot be used to generate a full route of flight for the flight path modeling module of the ACME. In these cases, the only option was to use a direct route of flight in place of unresolvable flight segments, even in the model of current procedures.

6.2 Analysis Methodology

With the generation of a complexity measure for ATC that has been specifically validated for both current procedures and free flight procedures, a number of follow-on analyses are necessary in order to examine some important issues. For example, given a set of flights flying from a set of departure airports to destination airports, it is important to understand the difference in ATC complexity between these flight operations when they are conducted under both clearance-based procedures and free flight procedures.

Such an analysis has been performed by the MITRE corporation, in support of the FAA. The results of this study showed that the density and proximity events of the traffic situation decrease under free flight procedures more often than they increase. The methodology used in the DIRECT study of ATC complexity under current procedures and free flight was designed to allow consideration of all major traffic characteristics, rather than just density and conflict events.

The traffic scenarios that were used for this analysis were derived from (SAR) data from Denver ARTCC. Efforts were made to obtain OAG scheduled flight data, but these efforts were unsuccessful. The previously referenced study was conducted with nationwide traffic scenarios derived from OAG data, which motivated the attempt to conduct this study with OAG data. Such an effort would provide a more direct comparison between the two studies.

Approximately six hours of SAR data was used for the traffic complexity analysis. This sample of SAR data was recorded on June 6, 1995. The SAR data contains all flight plans, flight plan amendments, remove strip and track messages that are generated by the ARTCC Host computer, in addition to a huge amount of other data that does not pertain to this study. The flight plans for each of the flights that passed through Denver ARTCC during the four hour time period on the sample date was used to generate a full flight trajectory in the ACME system. The ACME system has been developed specifically for this study to generate flight models and analyze the complexity of the resulting traffic situations. Two different fast-time simulation runs were conducted, one for current procedures and one for free flight. The same input set of flights is used for each of these runs, but different route models are used.

For current procedures scenarios, flight routes are modeled along ATC Preferred Routes as obtained from NFDC data. Direct routes are used in place of ATC Preferred Routes that cannot be completed from the NFDC data. For free flight scenarios, flight routes are modeled as direct flights from departure to destination. In both cases, little attempt was made to model accurate routes in the departure and arrival terminal area airspace. ATC complexities were not analyzed in TRACON sectors.

Complexity of the ATC traffic situation was analyzed for all sectors in Denver ARTCC's airspace. The 3-dimensional boundaries of the sectors were obtained from the Denver ARTCC Adaptation Controlled Environment System (ACES) data. The Fix Posting Area (FPA) record of the ACES data describes the boundaries of the airspace sectors. This data was processed and used in the ACME system to allow the determination of the airspace sector that an aircraft is in at each point in its flight. Once the entire set of flights that occupy a given sector at a given time instance is known, the ACME system applies the Complexity Measure to the ATC traffic situation. The measured complexity components, and overall complexity is then output to a file for post-processing analysis.

Once the complete set of complexities is available from the SAR data sample for each of the fast-time simulation runs, a comparison is made of average complexity components and overall complexities over 15 minute time intervals between the current procedures simulation run and the free flight simulation run. The first goal of this comparison is to attempt to validate the results of this study with the results of the MITRE study previously referenced. Since the two studies both attempt to evaluate the changes in density and proximity events under free flight, we expected to obtain similar results. The second goal of this comparison is to determine the change in *overall* ATC complexity between current procedures and free flight. Thus, three different complexities are evaluated in the comparison. The Density and Closest Approach complexity components are used to compare against the results of the MITRE study in changes in density and proximity events. It is important to note that the third type of complexity that is evaluated in this study is the overall complexity, which was not examined in the MITRE study.

6.3 Traffic Complexity Analyses

6.3.1 Current Procedures Vs. Free Flight

The density and the number of closest points of approach associated with current procedures and free flight were compared on a sector-by-sector basis across 15 minute time intervals (for these comparisons, the TRACON was considered to be one sector). A count was made of all cases in which the current procedures complexity was higher and cases in which the free flight complexity was higher. The results from a 6 hour System Analysis Recording (SAR) data sample are shown below. These results are accumulated over sectors and time intervals. Note that these results may not represent the same sets of sector measurements because cases in which the complexity does not change were ignored.

	CP > FF	FF > CP
DNS	293	274
CPA	344	338

Table 12. DNS and CPA Comparison - Current vs. Free Flight

Also note that a similar result is obtained here as in the previously mentioned study (Ball, et al., 1995). Both studies indicate that the free flight procedures decrease sector density and conflict events as compared to current procedures.

A comparison of the overall complexity between current procedures and free flight was also conducted. These results, again accumulated over sector and time intervals, are presented below.

	CP > FF	FF > CP
Overall	145	971

Table 13. Overall Complexity Comparison - Current vs. Free Flight

The results of this comparison indicate a substantial increase in the number of cases in which the overall ATC complexity is greater under free flight than under current procedures. Note that many more cases are involved in the comparison of overall complexities than in the comparisons of density and conflict events. This is caused by the fact that many more traffic characteristics are considered in the overall complexity measure, which results in fewer situations in which the complexity remains the same between current procedures and free flight.

This result provides a very strong indication that measures of density and conflict events are not sufficiently representative of the overall complexity of ATC. The differences in traffic characteristics - other than density and conflict events - have a significant impact on the difference in overall complexity between current procedures and free flight.

6.3.2 Complexity Dependencies Between Sectors

In our original traffic complexity analysis plan, we intended to examine the potential for dynamic dependencies and relationships of complexity factors between adjoining sectors. However, after interviewing the Air Traffic Specialists, we realized that this analysis would not be meaningful to perform. Controllers stated that the complexity of an air traffic situation depends upon the aircraft currently in the sector. Further, they stated that at any given time, they could be extremely busy (i.e., they would require the assistance of both a data-side and an additional radar Controller), but the Controller responsible for the adjoining sector would not be busy at all. These large differences in workload and/or complexity between adjoining sectors e a direct result of the characteristics of the traffic flows through the ARTCC airspace.

For example, if a large number of east-bound jets are simultaneously passing through high-altitude sector "A", then one can imagine that the complexity of control due to aircraft density (or simply the number of aircraft) might migrate across sectors, to sector "B," as the traffic moves eastward. However, this migration of complexity from "A" to "B" would only occur if the aircraft were all going to the same destination. If, as is normally the case, the aircraft are flying to a number of east coast destinations (both in the North and the South), then their respective flight paths would quickly diverge. Also, the potential conflicts experienced in sector "A" (e.g., the east-bound traffic crossing with arrival traffic) would most likely not occur in sector "B" because of the difference in traffic patterns. The complexity experienced in sector "B" would be greatly different from that of sector "A." Put simply, it would not be possible, nor would it make sense, to determine the complexity in sector "B" by evaluating the complexity in sector "A."

6.3.3 OAG Complexity

Throughout the course of the contract, Wyndemere tried a number of times to obtain valid OAG data for use in our analyses, as the OAG data would provide a more complete analysis of the nationwide air traffic situation. However, even after contacting both the VOLPE Transportation Center and the Denver ARTCC Facility, we were unsuccessful in obtaining the data. VOLPE had originally sent us a tape which, they assured us, contained OAG data. When we received the tape, however, the data was completely corrupt and subsequent attempts to contact VOLPE for a replacement data set went unanswered. The Denver ARTCC Facility, on the other hand, did not have the correct hardware configuration needed to electronically transfer the necessary data (i.e., tape, disk, etc.) and told us that there was no timely way to complete FAA procurement of the equipment to accomplish the task.

7.0 COMPLEXITY REDUCTION AND THE *DIRECT* CONCEPT

7.1 Complexity Reduction Heuristics

In addition to measuring complexity, as part of this study we also examined various methods for reducing that complexity, based on the characteristics of the identified complexity factors. For each of the complexity components, one or more heuristic complexity reduction methods were identified. These heuristics apply to potential flight path modifications that could be applied to aircraft to reduce the complexity of the air traffic situation for the Controller. The DIRECT System would use these heuristics within an iterative algorithm to reduce the complexity of the air traffic situation by reassigning sector airspace for the Controller.

It is important to note that the following complexity reduction heuristics are not intended to provide conflict resolution. Rather, the complexity reduction heuristics should provide some level of additional organization to the traffic flow, such that the Controller is better able to perform the conflict resolution task. In addition, the complexity reduction heuristics are intended to support the process of Dynamic Resectorization. Toward this end, the complexity reduction heuristics should also result in some level of delineation between major traffic flows, such that different sectors could be created to deal with independent traffic flows.

Also, as described in the Operational Procedures section below, flight path modifications will only be assigned to aircraft in order to cause the aircraft to enter a different sector than the one that it would otherwise traverse without the flight path modification. Thus, the only way that a complexity reduction heuristic will have an effect is if it is partially responsible for an aircraft being handed off to a different sector. Note that the flight path modifications and sector airspace definition will be an iterative process, so that moving an aircraft to a different sector may not necessarily be a significant move, if in fact the sector boundary is also being moved toward the subject aircraft. Although the generation of the new flight path after a flight path modification heuristic is beyond the scope of this study, each of the heuristics will result in a unique flight path for aircraft. The combination of these suggested flight path modifications into a single flight path will be the subject of future work.

In the following subsections, each complexity factor is identified, briefly defined, and is followed by one or more complexity reduction heuristics. Some of the complexity reduction heuristics have been analyzed through the creation of scenarios that demonstrate the effectiveness of the heuristic in reducing the complexity of the air traffic situation. The analysis of these scenarios through the ACME system will be described within the description of the applicable complexity reduction heuristic.

7.1.1 Aircraft Count (ACT)

As mentioned above, this complexity component is simply a count of the number of aircraft within the lateral and altitude boundaries of the sector at an instant in time. A simple heuristic that could be used to reduce the complexity associated with the number of aircraft would be to force some aircraft to avoid the sector in question altogether. This sector avoidance heuristic could be implemented far enough ahead of time so that the number of aircraft in any given sector does not exceed some capacity limit - defined by other sector and traffic characteristics.

7.1.2 Convergence Angle (ANG)

This complexity component is a measurement of the severity of each conflict situation based on the conflict geometry. Obviously, then, a heuristic that could be employed would be to modify aircraft flight paths that result in high complexity conflict geometries so that the flight path conflict geometries will result in lower complexity. The benefit of using this heuristic is that in some situations, the complexity of the conflict will simply be reduced, but at other times, such a flight path modification may result in a complete avoidance of the conflict.

7.1.3 Crossing Altitude Profiles (CAP)

This complexity component is a count of the number of pairs of aircraft in which one aircraft will be climbing and one aircraft will be descending through the same altitude. One possible heuristic to reduce this type of complexity would be to simply modify certain aircraft (for example, all descending aircraft) flight paths so that they avoid the sector in which a number of aircraft are ascending. This is very similar to the method currently used in today's system. The main problem with this heuristic, however, is that it has the potential to be somewhat inefficient due to the static nature of the sector boundaries. An alternative heuristic could be to separate climbing and descending aircraft into separate streams.

7.1.4 Climbing or Descending Aircraft (CoD)

This component is a count of the number of aircraft that are climbing or descending at an instant in time. The same heuristics identified for Crossing Altitude Profiles, described above, could be applied to reduce the complexity due to this factor. Note that there is evidence from the Focus Group Interviews and simulations that the complexity increases as the number of aircraft in climb/descent situations increases, up to a certain threshold. Beyond this threshold, the complexity again begins to decrease. For example, if *all* aircraft in the sector are descending, that traffic situation can actually be less complex than a traffic situation in which some aircraft are climbing and some are descending.

7.1.5 Closest Points of Approach (CPA)

This complexity measure is a weighting of the number of aircraft that are within a threshold separation of each other at an instant in time. Note that the complexity reduction heuristics for this complexity component are designed to strategically reduce the significance of this complexity component in the target sector. Thus, a complexity reduction heuristic in this case is not intended to modify the flight paths to resolve the conflict because that would be a tactical maneuver (as least as far as this study is concerned).

The use of a complexity reduction heuristic such as strategic conflict avoidance is not intended to resolve a particular conflict but is used to provide an incremental movement away from a conflict. In the context of the DIRECT System, this heuristic would be weighted by the impact of the Closest Approach complexity component itself, and compared to the suggested flight path modifications of the other complexity reduction heuristics. The incremental movement away from the conflict may provide reinforcement for the flight path modification suggestions of other complexity reduction heuristics. The impact of this complexity reduction heuristic needs to be combined with other heuristics to be effective because flight path modification is only applied to move aircraft from one sector into another. In general, the incremental flight path modification away from a conflict will not cause the aircraft to move into a different sector.

Note that the flight path modifications that are associated with this heuristic may be either lateral or vertical changes. If the nominal flight path of an aircraft that is involved in a predicted conflict situation will be descending shortly after a predicted conflict, a flight path modification to descend earlier may be suggested, resulting in a vertical flight path change.

7.1.6 Aircraft Density (DNS)

Aircraft Density is simply the aircraft count divided by the sector airspace. The same complexity reduction heuristic as described for the Aircraft Count complexity component - changing an aircraft's flight path so that it avoids the sector of high complexity - also applies to the Aircraft Density complexity component. However, another heuristic that could be employed would be to increase the sector airspace allocated to the target sector. This would provide additional airspace to the Controller to increase the degrees of freedom available for aircraft maneuvering. Note, however, that this heuristic does not necessarily guarantee a reduction in the complexity. If this heuristic is applied without any other traffic modifications, it is possible for the result to be the inclusion of additional aircraft in the sector--a result that could even increase the contribution of this complexity component to the overall complexity.

7.1.7 Intent Knowledge (INT)

The level of information about the intent of the aircraft is rated in this complexity factor. The measurement of this factor is somewhat simplistic at the current time, being classified into three levels of intent knowledge - current procedures, half free flight and full free flight, as explained in section 4.4.2. The complexity for each aircraft associated with intent knowledge of current procedures is zero, full free flight is one, and half free flight is one-half. The half free flight case assumes an interim implementation of free flight in which destination, altitude, and airspeed information is known through a flight plan, and the deviations from those parameters is limited.

A complexity reduction heuristic that may be employed to reduce the complexity associated with this factor would be to modify flight paths of certain aircraft to avoid sectors of high complexity. However, since unrestricted flight paths is a basic tenet of the free flight philosophy, another appropriate heuristic could be to make modifications to the system so that Controllers would have better, more accurate Pilot intent information. This would most likely result in changes being made to Controller displays and to the communication systems being used for Air Traffic Control.

7.1.8 Aircraft Neighboring Conflict (NBR)

For each instant in which two or more aircraft are predicted to be within a threshold separation, a count is made of other aircraft that are within the general area of the potential conflict. Again, a method of strategic conflict avoidance could be employed to reduce the complexity associated with this factor. This heuristic suggests flight path modifications for aircraft that are considered to be 'neighbors' of a predicted conflict. These flight path modifications will move the neighboring aircraft farther away from the conflict situation.

7.1.9 Conflict Near Sector Boundary (PRX-C)

This complexity component is a count of the predicted conflicts that will occur within a threshold distance of a sector boundary. One quick reduction of this complexity would be to simply move the conflict location so that it was not as close to the sector boundary in question. Again, however, this would require altering aircraft flight paths, thereby reducing the amount of free flight an aircraft is allowed. Alternatively, the DIRECT System could suggest the temporary modification of sector boundaries to reduce the complexity. Whether one or more boundaries were changed would depend on the nature of the traffic within the target and adjoining sectors.

7.1.10 Altitude Variation (VAA)

This component is a measure of the variability of altitude of all of the aircraft in the sector at an instant in time. There was no evidence that this complexity component had an impact on the overall air traffic complexity. Thus, it was not included in the overall complexity measure, and no complexity reduction heuristics were identified.

7.1.11 *Heading Variation (VDF)*

This component is a measure of the variability of heading of all of the aircraft in the sector at an instant in time. One possible strategy to reduce the complexity of traffic based on aircraft heading differences is to redirect the aircraft into streams. Although this complexity reduction heuristic may not actually reduce the significance of the Heading Variation complexity component itself, it may result in complexity reduction in other components.

7.1.12 *Speed Mix (VAS)*

This component is a measure of the variability of speed of all of the aircraft in the sector at a time instant. Again, a possible heuristic to reduce the complexity associated with many aircraft flying at different speeds is to force the aircraft into speed-based streams.

7.1.13 *Aircraft Proximity to Sector Boundary (PRX)*

This complexity component is a count of the aircraft that are within a threshold distance of a sector boundary at a given time instant. The complexity reduction heuristics applicable to this factor are similar to those used for the Conflict Near Sector Boundary (PRX-C) factor. First, we could simply alter the aircraft flight paths so that they are not as close to the sector boundary in question, but again, this would require altering aircraft flight paths, thereby reducing the amount of free flight an aircraft is allowed. Therefore, the DIRECT System could be used to suggest the temporary modification of sector boundaries to reduce the complexity. Again, whether one or more boundaries were changed would depend on the nature of the traffic within the target and adjoining sectors.

7.1.14 *Airspace Structure (STR)*

This complexity component measures the conformance of the traffic flow through a sector to the geometry of the sector. A major axis and aspect ratio are calculated for the sector, and then the difference in heading between each aircraft and the major axis is computed. The squared deviation from the major axis of the sector is weighted by the aspect ratio and then summed over all aircraft.

A simple heuristic to reduce the complexity due to this factor is, of course, to force aircraft that would be flying "against the grain" of the sector to avoid that sector completely. Another heuristic is to assign aircraft headings that would force aircraft to fly in line with the major axis of the sector. However, both of these heuristics require aircraft to modify their headings, thereby reducing the number of aircraft allowed to be in free flight. Therefore, another possible solution would be to change the shape of the sector so that the major axis follows the general traffic pattern.

7.2 Operational Procedures and DIRECT Implementation

This section of the document will describe the operational procedures that will govern the use of the Dynamic Resectorization and Route Coordination (DIRECT) concept that has been referred to in this study. In many cases, the operational procedures described below will simply outline a set of potential procedures, from which a selection will have to be made once the concepts of Dynamic Resectorization and Free Flight mature.

The DIRECT System will analyze the dynamic traffic situation and generate modified aircraft flight paths and dynamic airspace sector boundaries. Both the flight path modifications assigned to aircraft and the sector boundary changes will be generated with the goal of reducing the complexity of the traffic situation in all of the sectors that are affected.

Note that the flight path modifications are not intended to provide automated conflict resolution and will generally be at a more strategic level. Flight path modifications will only be assigned to aircraft to cause the aircraft to enter a different sector than it otherwise would without the flight path modification. The operational philosophy of the DIRECT concept is that the situation within a sector is the responsibility of a single Controller. Automated advisories and flight path changes will not be generated automatically by the DIRECT System in order to resolve a situation within a single sector. Rather, the goal of the system is to form sectors within which the Controllers will be able to provide separation assurance, and can re-assign aircraft to different sectors if necessary to allow a reasonable complexity level.

The intent of the DIRECT concept is to maximize the free flight flexibility provided to aircraft, while still maintaining an acceptable level of complexity for the Air Traffic Controller who must assure aircraft separation. Thus, the operational procedures that govern this concept focus on the means by which the limitations to that flexibility are communicated to both Pilot, Controller and the Airline Operations Center (AOC). These limitations on Free Flight flexibility will be communicated to the ATM system operator through new information and procedural elements, which are described below.

7.2.1 Controller Elements

7.2.1.1 Changes to Sector Boundaries

The DIRECT concept will cause the Controller's airspace to change to accommodate various traffic characteristics. To be able to handle these airspace changes, the information displays available to Controllers will also need to change. For example, sector boundaries will most likely have to be depicted on the Controller's display. In making this information available, Controllers will be better able to compare aircraft positions to the dynamic boundary position. Also, in addition to displaying the current position of the Controller's sector boundaries, it will be necessary to display some detailed information about the future progression of sector boundaries. The Controller can use this information to predict when an aircraft will be entering and leaving the sector, and to correlate the future sector boundaries with aircraft flight paths.

7.2.1.2 Frequency of Boundary Changes

The frequency with which sector boundaries can be changed is also an important issue to address. We will need to establish a maximum number of sector boundary changes that can be handled in a given day--a number most likely constrained by the amount of procedural work that needs to be completed in order to successfully alter sector boundaries. In addition, the number of allowable sector boundary changes will also be influenced by the cognitive limitations of the users (especially the Air Traffic Controllers) of the system. Pilots may not be as greatly impacted by continually changing airspace structures as Controllers primarily because for the most part, Pilots will fly in and out of that airspace only a limited number of times throughout a given day. Controllers, however, will be responsible for understanding the current airspace structure for entire 8 hour work shifts. If this structure continually changes, the Controllers will most likely spend the bulk of their time learning the new airspace structures, rather than controlling traffic.

7.2.1.3 Predicted Aircraft Flight Paths

The free flight concept makes the prediction of aircraft flight paths and intentions much more difficult than in current, clearance-based flight procedures. However. the DIRECT System concept will make the need for flight path predictions even more essential, in some cases. Since the DIRECT System will be using predicted aircraft flight paths to suggest sector modifications, Controllers and/or Traffic Managers will need to be able to view the predicted aircraft flight paths to assess the DIRECT-generated suggestions.

7.2.1.4 Limitations Placed on Aircraft Flight Paths

The DIRECT concept will provide aircraft flight path information for select aircraft, designated by the Controller. If flight path restrictions are placed on an aircraft by the DIRECT System, those flight path restrictions will need to be displayed to the Controller. These flight path restrictions will generally be high-level, strategic restrictions, designed to keep an aircraft inside one sector, and outside of another sector or other airspace area. However, if the controller does not have this information, s/he will not have a complete understanding of the traffic, and therefore his/her workload level would most likely increase.

7.2.1.5 Flight Rules (Free Flight or Clearance Based)

In the event that the Controller has a mix of free flight and clearance-based aircraft occupying his/her sector (as may be the case until all aircraft are free flight equipped), it will be important for the Controller to be able to quickly make this distinction. Based on our simulations, Controllers handle free flight aircraft differently than clearance-based aircraft, primarily by maintaining a greater amount of separation space "around" free flight aircraft. If the Controller is currently experiencing a period of high traffic density, it will be important for him/her to know which aircraft must be separated by a greater amount than usual, to maintain safe separation. In addition, with dynamic sector boundaries Controllers will need to know which aircraft have the potential (due to free flight) to actively change sectors so that coordination between Controllers can remain as proactive as possible.

7.2.2 Pilot Elements

7.2.2.1 Communications

Although under the DIRECT System, Controllers will most likely still issue communications channel changes to Pilots, it may be helpful for Pilots to know that sector boundaries have changed and therefore, the communication frequencies associated with those new sector boundaries may also have changed. If a Pilot is very familiar with a certain airspace configuration (i.e., shuttle Pilots flying between San Francisco and Los Angeles), then it is highly likely that the Pilot is also familiar with the frequencies associated with each sector. Under the DIRECT System, the dynamic sector boundaries and corresponding frequencies will need to be communicated to the Pilot to ensure that s/he will still be able to communicate with each Controller.

7.2.2.2 Routing Changes

In much the same way that a shuttle Pilot may become familiar with frequently used communication channels, it is even more likely that the Pilot would be familiar with standardized routings between destinations. However, the DIRECT System may suggest that the routing taken by all shuttle aircraft be modified to go around a particular sector boundary, based on traffic characteristics. In this example, the VORs and fixes which may have been so familiar to the Pilot are no longer used, if only temporarily. In this case, the Pilot will need to be made aware of the new waypoints used in the modified routings, to ensure a trouble-free flight.

7.2.2.3 Flight Rules (Free Flight or Clearance Based)

Again, in the event that there is a mix of free flight and clearance-based aircraft occupying a particular sector, it will also be important for Pilots to be able to quickly know which aircraft have free flight capability. If certain aircraft are operating under clearances and the sector boundaries change, then the Pilots will need to know that those aircraft paths might also change, to correspond with the sector changes. Similarly, free flight aircraft may not be required to modify their flight paths to match a sector boundary change, and this information must be made available to other pilots.

7.2.3 *AOC Elements*

7.2.3.1 Proposed Aircraft Flight Path Limitations (For Potential Negotiation)

At times, the DIRECT System will identify flight path modifications to be made to specific aircraft, to maintain acceptable levels of complexity across sectors. For example, the DIRECT System might suggest that 2 of 3 aircraft from Airline XYZ (Aircraft #1 and #2) be re-routed into another sector. DIRECT could send this information to the Dispatcher for that airline so that s/he could compare the suggested modifications against the company's current goals. It may be the case that the dispatcher would rather that Aircraft #2 be remain on course (to meet connecting flight times, etc.) and that Aircraft #3 be rerouted. This information could be fed back into the DIRECT system so that the appropriate changes could be made.

7.2.3.2 Predicted Areas of Flight Path Limitations Due to Complexity

Because it will have predictive capabilities, the DIRECT System could also contact the AOCs to let them know that at some point in the future, certain sectors may be overloaded. The AOCs could use this information to personally reroute their aircraft around these sectors, thereby reducing the chance that the affected sectors would be overloaded, reducing the possible flight path changes that their aircraft would have to execute, and possibly reducing their flight times and delay times.

7.3 DIRECT Concept Exploration

In analyzing complexity, we have identified a number of heuristics that could be employed to reduce the complexity associated with each complexity factor. These heuristics are: Sector Avoidance, Change Conflict Geometries, Create Aircraft Streams (based on speeds, headings, or climbing/descending aircraft), Move Conflicts, Temporarily Move Sector Boundaries, Increase Airspace, and Change Sector Shape.

A number of these heuristics, however, require that Controllers restrict or alter one or more aircraft flight paths in order to reduce the complexity. Although many current Air Traffic Control procedures result in aircraft having to deviate or alter their flight paths, these types of strategies will not be favorable in a free flight environment. However, we have seen through our simulations of free flight that Controllers will not simply let all aircraft fly under free flight procedures if they (the Controllers) are to remain ultimately responsible for ensuring separation. In our simulations, the Controllers ended up assigning flight path restrictions to any aircraft that could possibly result in a conflict situation (see Section 6, below). Instead of being able to handle more aircraft, we saw that this increased amount of communication somewhat limited the number of aircraft Controllers were able to monitor.

One of the commonly held misconceptions about the DIRECT concept is that it is merely a tool which will dynamically alter sector boundaries. However, the intent of the DIRECT project is to provide Air Traffic Specialists with both a "Dynamic Resectorization" *and* a "Coordination Technology" tool. One can imagine many cases in which only one or two aircraft are problematic in achieving the goal of separation. In this case, it doesn't necessarily make sense to completely change the shape and/or size of the sector to accommodate one or two aircraft. Therefore, the DIRECT System can provide the Air Traffic Specialists with the ability to coordinate the modification of aircraft flight paths (for example, the aircraft could be automatically handed off to an adjoining sector after the appropriate system-assisted coordination had been established). In providing computer assistance for hand-offs, the affected Controllers spend less time coordinating, and more time controlling or monitoring traffic. In addition, the DIRECT System could also be used to coordinate aircraft routing with AOCs, to reduce Controller workload, air traffic complexity, and flight delays.

The example above describes what the DIRECT System might do if the cause of the complexity was only a few aircraft. However, in the case where the complexity of the situation is due to the current flight characteristics of a number of aircraft, the DIRECT System might in fact suggest modifications to be made to the sector boundaries. For example, if, in the current traffic situation, a number of aircraft are flying "against the grain" of the sector, causing the Controller to experience a high level of complexity, then perhaps that complexity could be reduced if the Controller's sector was dynamically redesigned to match the current traffic flow.

Of course, sector redesigns would most likely **not** occur on a continual basis, but it may be possible to identify future traffic periods (arrival rushes or departure pushes, for example) for which alternate sector design patterns would be more appropriate. In this case, the DIRECT System would provide the necessary information and coordination assistance to allow the Air Traffic Specialists to effectively and quickly change the sector responsibilites in order to meet the predicted change in traffic. It is important to note that not all boundary modifications would occur in isolation of modifications made to aircraft flight paths. Rather, the DIRECT System might provide suggestions which would result in a slight modification made to the sector boundaries *combined* with some modifications made to select aircraft flight paths. In performing both of these actions, an optimal solution can be reached which reduces the complexity placed on the Controller, maximizes the use of airspace, and allows more aircraft to continue flying under free flight procedures.

7.3.1 DIRECT Example

One of the important goals of our study was to evaluate our complexity measure in sectors *other than* the one used during the simulation. In certain cases, the scenarios used for the simulations were substantially different from real traffic scenarios simply because we were to trying to analyze specific aspects of ATC complexity. As part of the DIRECT concept exploration, we decided to further evaluate our complexity measure in other sectors, using uncontrolled aircraft flight tracks, flying under free flight (i.e., direct flight routes) procedures.

As an example of how the DIRECT system and the complexity measure might be used, consider the following example taken from a 6 hour SAR data file (June 6, 1995) from Denver ARTCC, with all aircraft flying free flight (direct) trajectories. For this example, we will be discussing Sectors 8 and 9, which are located to the east of DIA (see highlights in the figure below), instead of Sector 29, which was used for the simulations. Sector 9 is located north of Sector 8.

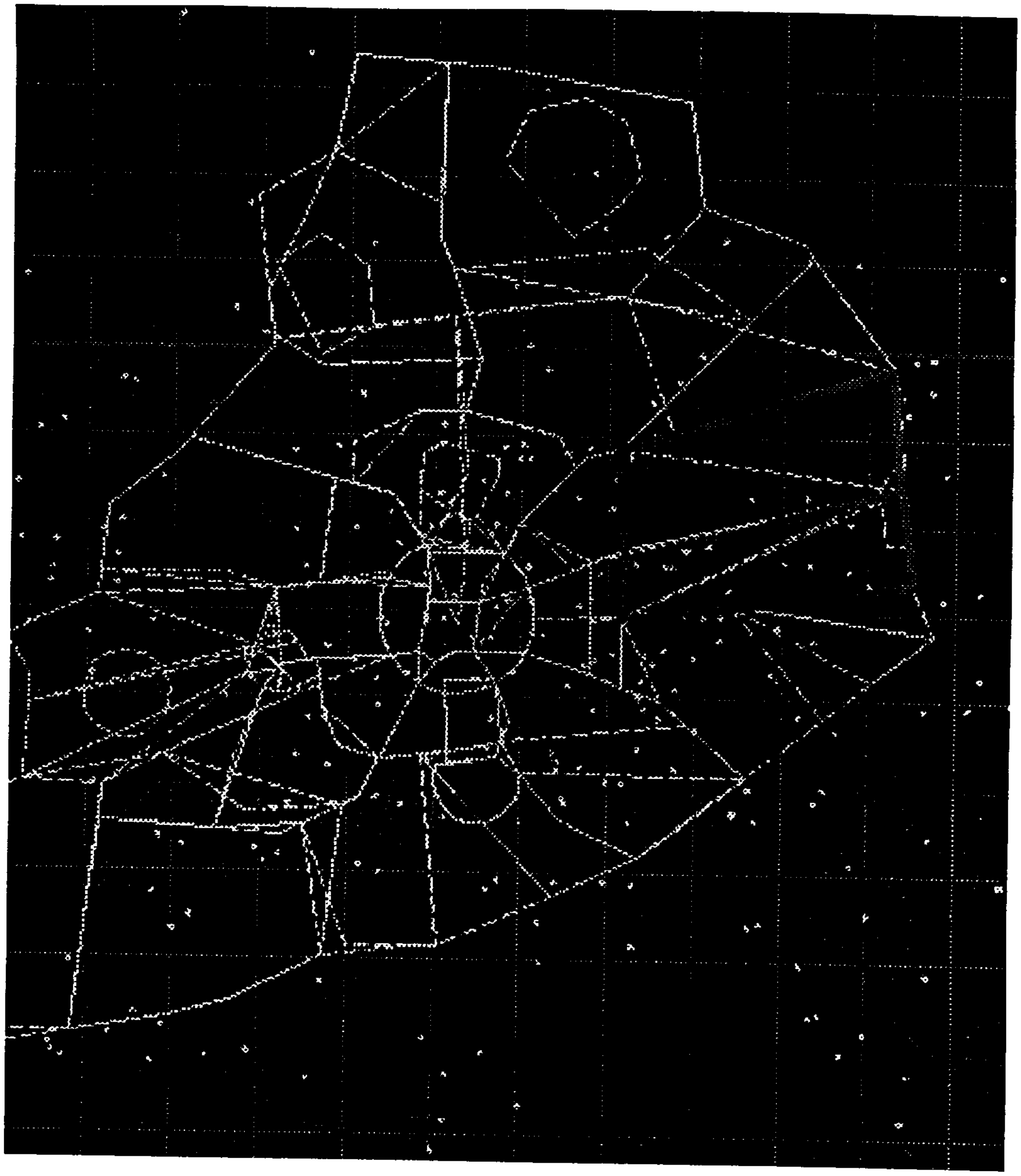

Figure 15. Sectors 8 and 9 in Denver ARTCC

The following figure shows a detailed view of ZDV8 and ZDV9 for June 6, 1995 at 17:39:55 UTC. Note that the displayed aircraft have been modified to be flying direct flight paths from their departure to destination airports.

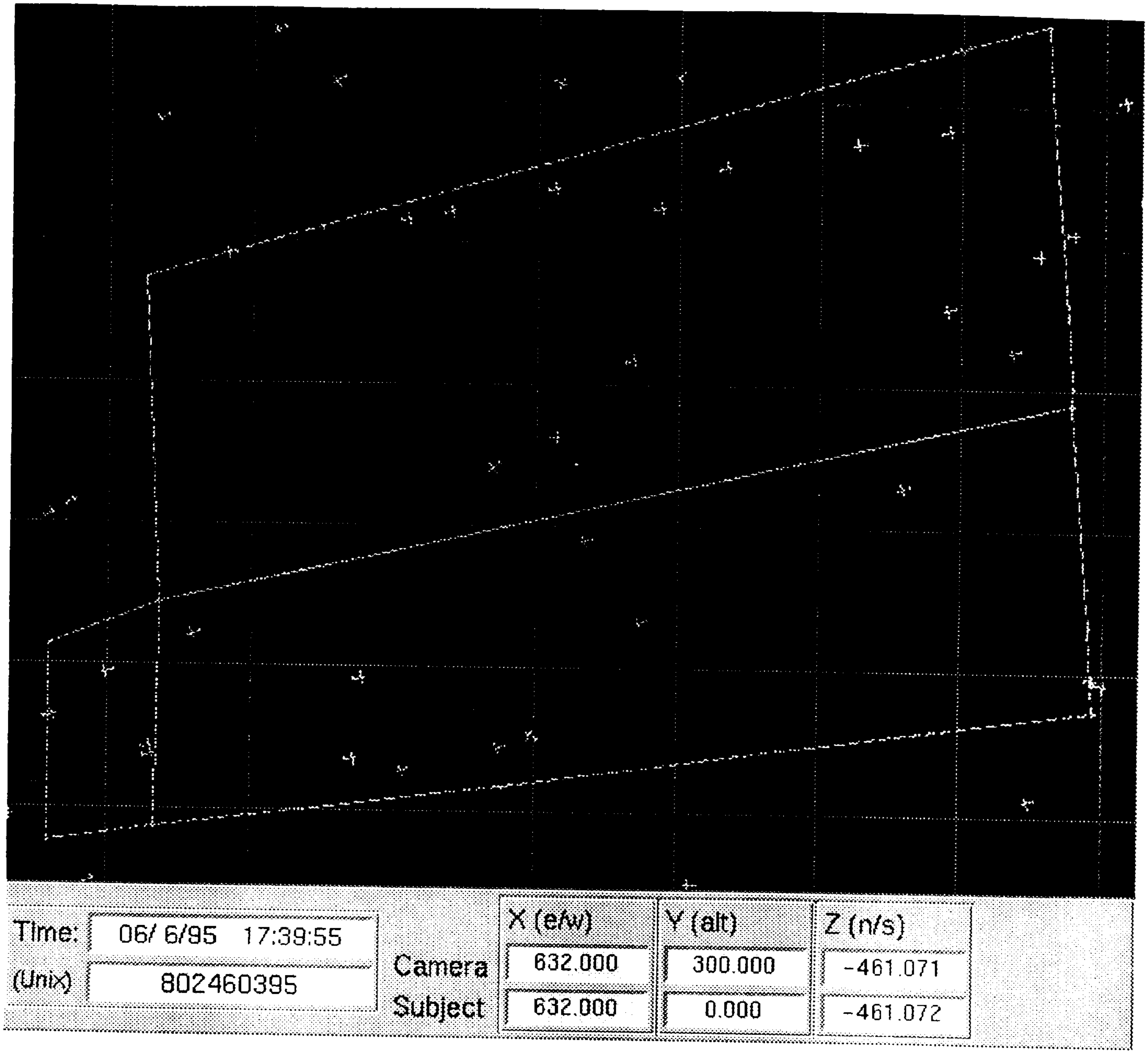

Figure 16. Original Sectorization for ZDV8 and ZDV9

The two figures below show identical individual complexity factors, as well as the overall complexity computation, for both Sectors 8 and 9. Note that in these two figures, the current time (as shown in the figure above) is depicted by the left axis. At the current time, for ZDV8, the overall complexity is approximately 15.8 (Figure 17). For ZDV9 at the same time, the overall complexity is approximately the same value (Figure 18).

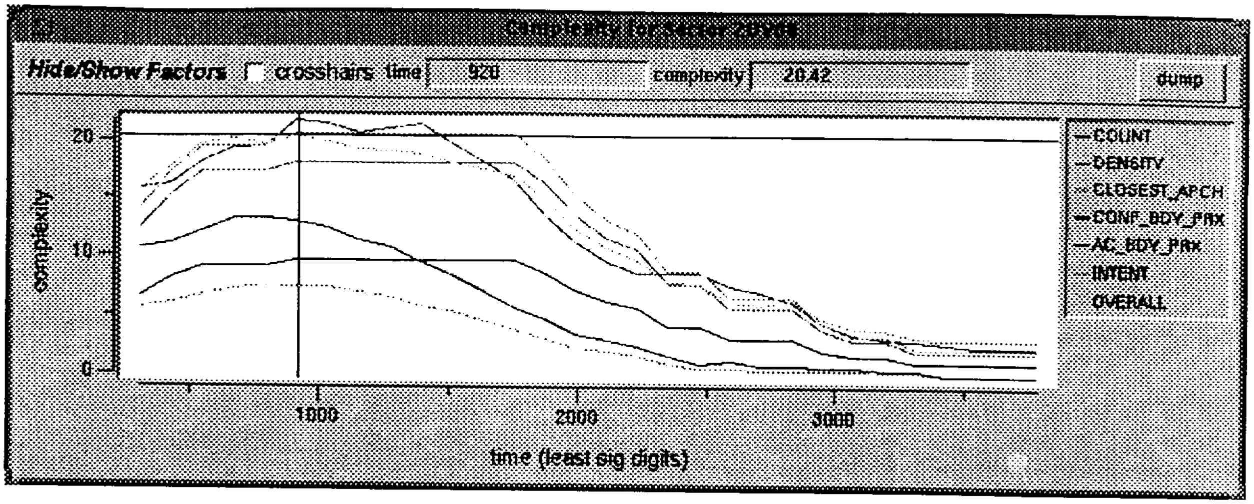

Figure 17. Original Complexity for ZDV8

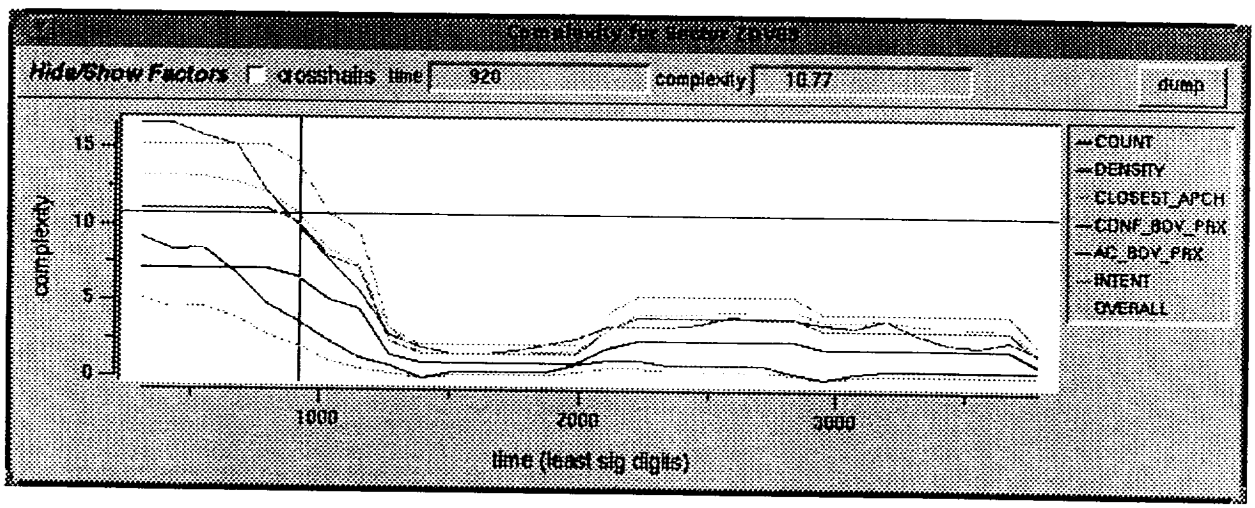

Figure 18. Original Complexity for ZDV9

In the above figures, note that approximately 9 minutes into the future, the overall complexity for ZDV8 is expected to increase to 20.42, and slightly decrease to 10.77 for ZDV9. In addition to the expected change in overall complexity, note that the complexity associated with conflict boundary proximity (PRX-C), in ZDV8, will be approximately 12.5 (an increase from approximately 10.1 at the current time).

The figure below (Figure 19) shows the corresponding future traffic situation, using this original sector configuration.

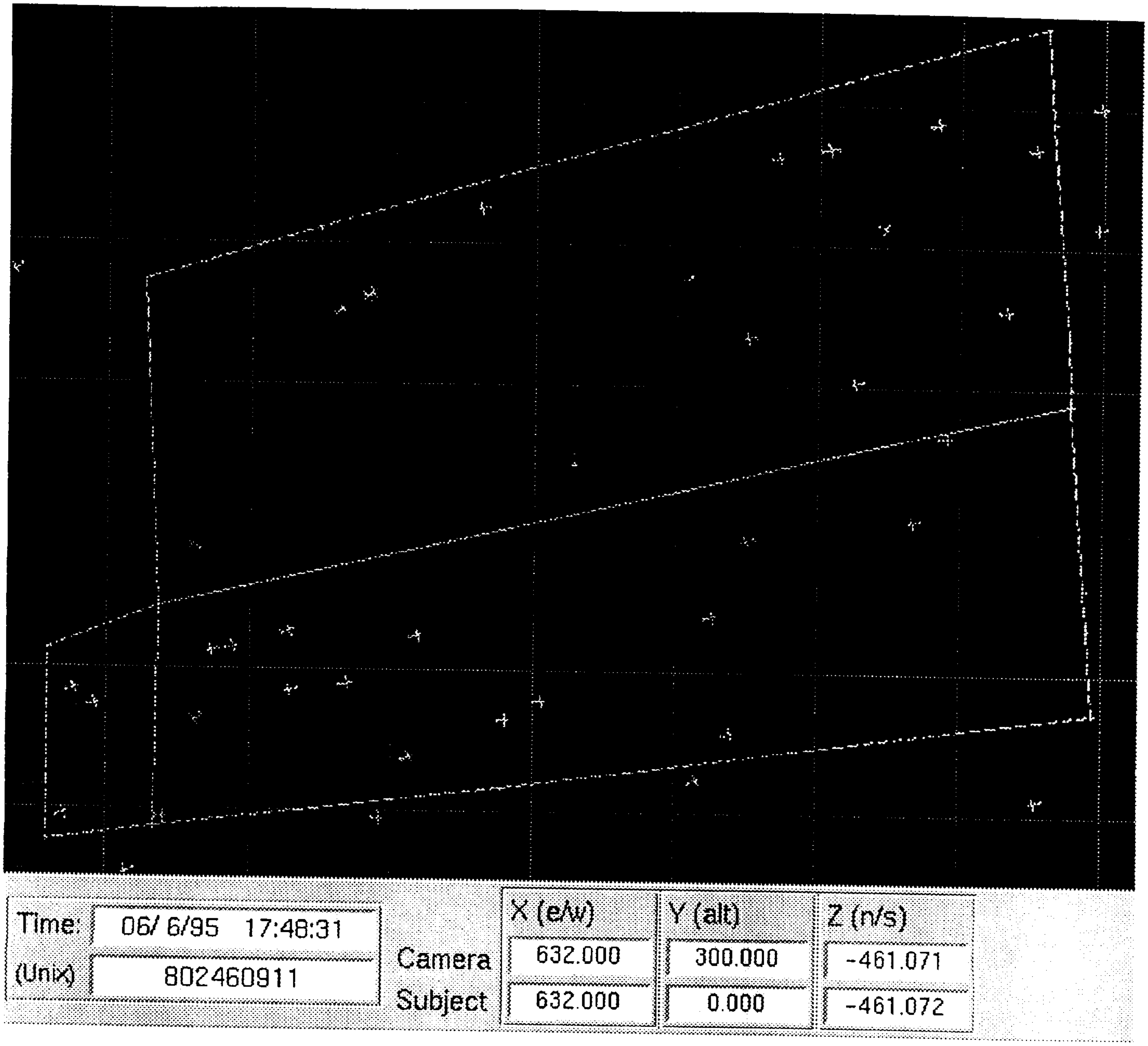

Figure 19. Traffic Situation Approx. 9 Min. Into Future

Note that there is a large amount of both arrival and departure traffic in the west end of ZDV8, with very little airspace available for maneuvering. Also note that there are a number of aircraft which are predicted to be flying close to the northern boundary of ZDV8, for the entire time they are in the sector.

The DIRECT system would use the predicted complexity information to suggest alternate (or simply modified) sector boundaries that would better suit expected traffic patterns. In the current example, there are a large number of aircraft arriving into DIA through ZDV8. However, there are enough departing aircraft in the sector to cause some problems. If the system were to be used to modify the northern boundary of ZDV8, for example, the Controller would have more airspace available for routing the departing aircraft around the arrivals, thereby ensuring that the arriving aircraft would not get any more delay than necessary for in-trail separation. In this example, the departing aircraft could perhaps be moved a bit northward, without requiring the ZDV8 Controller to coordinate the route change with the Controller from ZDV9.

The figure below (Figure 20) shows this modified sector configuration. Although we haven't shown it in this example, note that the ZDV8 Controller would now have more room near the northern border of the sector for routing the departing aircraft.

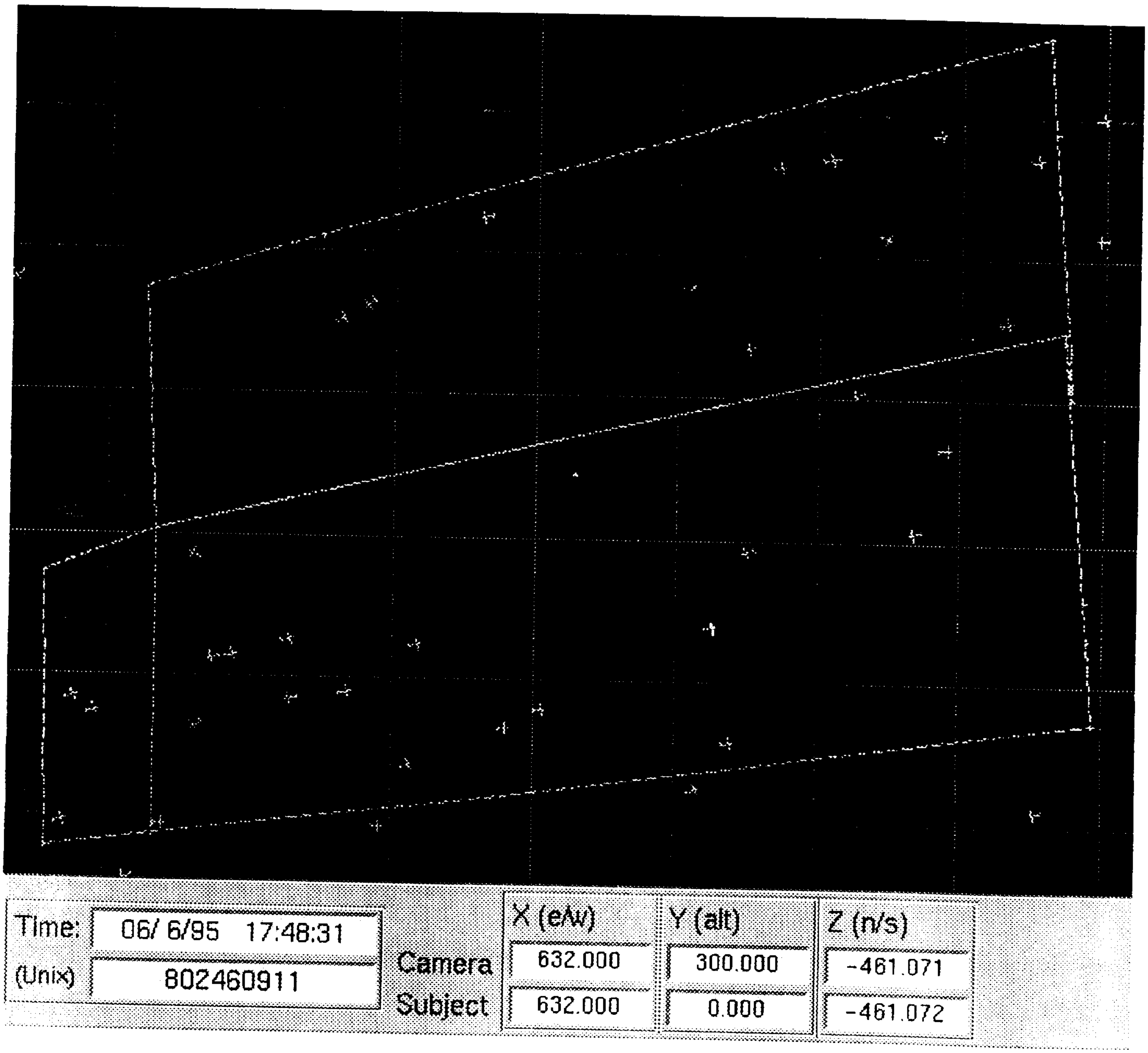

Figure 20. Future Traffic Situation With Modified Sector Boundaries

The two plots below show the resulting complexity measures if the sector boundaries had been changed as described. The following two figures have the same time scale as figures 17 and 18 above. The left axis is the current time (17:39:55 UTC), and the crosshairs show the complexity measures approximately 9 minutes into the future (i.e., 17:48:31, as shown above in Figure 20).

Note that the overall complexity for ZDV8 would decrease to 17.91, without increasing the overall complexity for ZDV9. Also note that the complexity associated with the conflict boundary proximity measure (PRX-C) decreases as well.

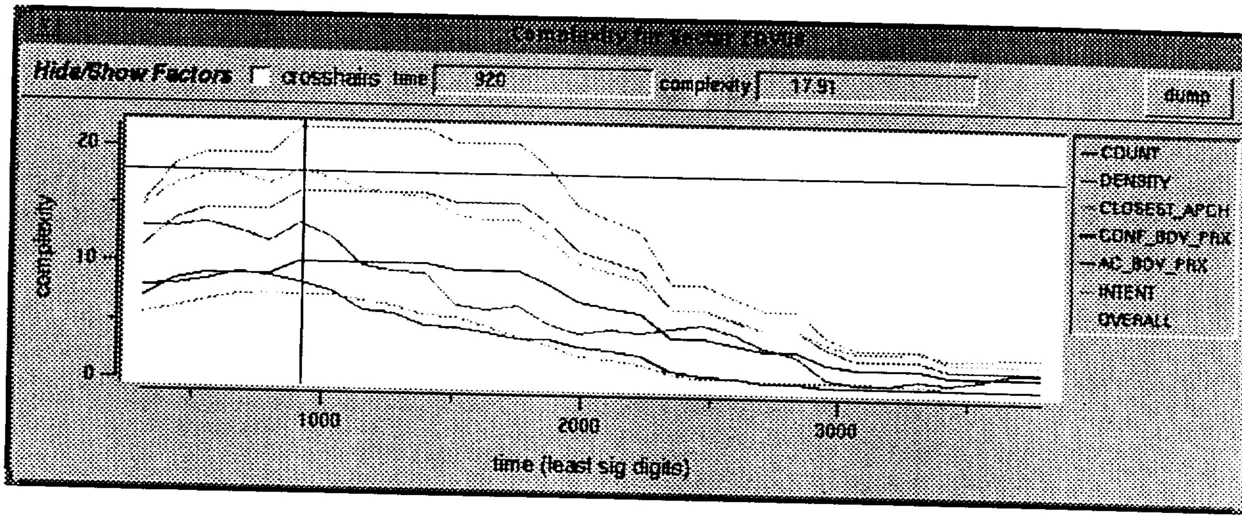

Figure 21. ZDV8 Complexity With Modified Sector Boundaries

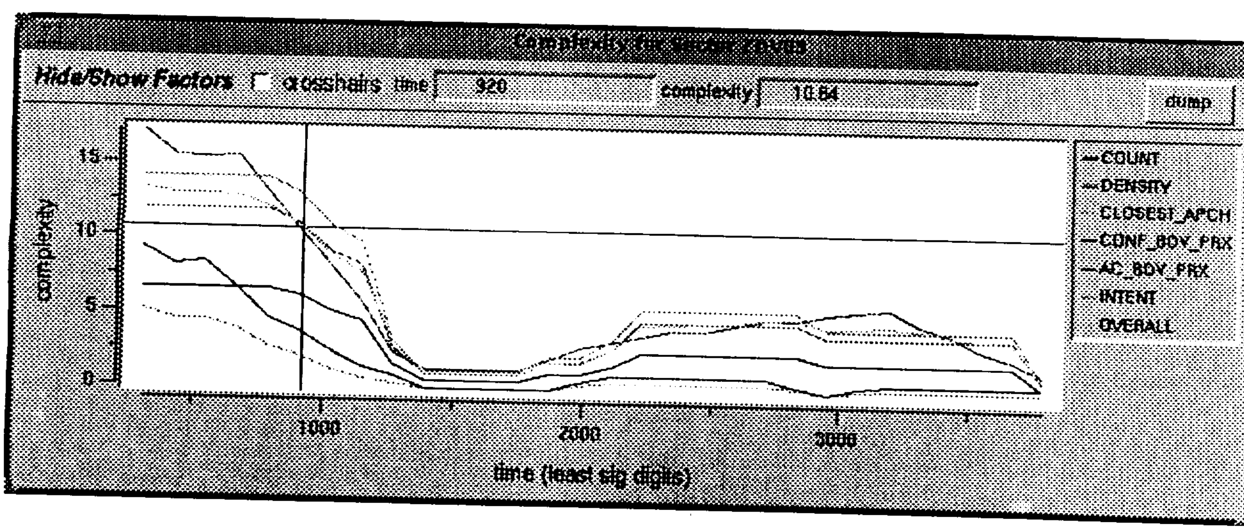

Figure 22. ZDV9 Complexity With Modified Sector Boundaries

8.1 Simulation Debriefing Comments - Future ATC Systems

The comments presented below, collected after the simulation sessions, provide some examples of the concerns Controllers have regarding the transition to a free flight environment. These statements are not intended to discourage current efforts towards a free flight system. Indeed, almost every Controller stated that a free flight system would be possible and workable - as long as they were provided with useful and usable tools to help them maintain separation and situational awareness. As new research efforts are proposed and existing efforts continued, it is important that we remember to include the system users, both Pilots and Controllers, in our design suggestions and decisions. In doing so, we increase our potential to create a system that can reduce the complexity placed on the users, reduce the amount of restrictions placed on aircraft, and increase the safety and efficiency of our nation's air traffic system. The statements below can therefore be used as design considerations to help focus new technologies (such as Controller display aids) and aid in the overall modernization of the current system.

8.1.1 Intent Information

A number of comments were collected which reflect the importance Controllers place on having intent information (from both Pilot and Controller) for effective control. After a particularly difficult free flight scenario, one Controller stated:

- "You have to have some idea of what the Pilot...what he wants to do...that has got to get to the Controllers, that has got to get to the person who is responsible. I'll tell you what, if two Pilots were flying along and they were using their TCAS - let's say TCAS goes out to 100 miles - and they can see that they're both less than 2000 feet, and that they're going to get the same punishment that *I* would get if they get within 5 miles and less than 2000 feet, the first thing those two Pilots are going to want to know is, 'what's the other guy going to do?'... You have to have some way to have a plan. And when nobody knows the intentions of the players involved, then you can't make that plan...and that's what we've got to get around in free flight...we've got to get some way to get the intentions of the aircraft."

This reliance on intent information was seen throughout the simulations, and it needs to be stressed that this intent information *must* be available in a timely manner. As we saw in our simulations, without the ability to look far enough ahead in time to understand the intent of our simulated Pilots, some Controllers were inclined to individually assign headings and altitudes to *all* aircraft just so that they were able to predict the future locations of these aircraft. This unpredictability of a free flight system was a major issue with all of our simulation participants, and they all stated that in order to effectively control aircraft in such a system, certain unfavorable precautions might need to be taken:

- C1: "You can only be calculating...or worrying about 2 or 3 of them (potential conflicts) at a time. You can't be worrying about 12 or 14 of them. ...And then after you fix it (a potential conflict), then you believe it's fixed and you don't worry about it...you say, 'this one's good,' and then you go worry about the other ones that are coming up. But if you have to go back each time and worry about whether it's still good or not, then you're going to end up with us talking to *every* airplane and telling them *exactly* what we want them to do through our sector unless they are a county away from everybody else."

  C2: "And since we won't have time to do that, we're going to effectively double the required separation...I'm not going to sit here and tell every airplane what to do *twice*...'I want you to do this for the next 30 minutes and then when you're done, you can go back so the next Controller can tell you to do the same thing for the next 30 minutes.' I'm just going to over-separate them and...that's probably not what they'd like."

The level of importance that Controllers placed on timely aircraft intent information should be reflected in the design of a free flight system. Whether the changes are incorporated into the current equipment (i.e., FDADs, VSCS, etc.) or designed into future systems (such as DSR and STARS), the communication of intent is a requirement of Controllers that needs to be addressed. There must exist a method for Controllers to be able to accurately predict future aircraft positions in order to maintain system safety and to be able to sustain effective control of a free flight system.

8.1.2 Communications and Workload

Controllers expressed concern about how both their mental and physical workload levels might increase under free flight. In addition, they stated that if they are to share the responsibility for separation with Pilots (as described in the RTCA document), they would like the Pilots to be equally accountable for violations of that separation.

Controllers also feel that verbal communications would most likely increase under free flight:

- "I'm going to have to re-clear every airplane that enters my sector, that I think could *ever* get together (conflict) with somebody else, to maintain *something* so that before he leaves, I can tell him, 'OK, go back to what you were doing before...' He goes to the next Controller, and he's going to be told the same thing....I think that is a big issue."

Given this Controller's assumption, certain communication systems would need to be refined. For example, it will be important to devise alternative means for Controllers to coordinate between themselves, rather than using verbal communications. In addition, it will be important to then provide an effective way for the Controllers to communicate this coordinated information to Pilots. These coordination alternatives will be especially critical during periods of high complexity. Perhaps by using a system, such as DIRECT, which provides automatic point-outs of traffic and potential conflicts that are near, but outside of sector boundaries, Controllers will be able to focus more on traffic that is actually in their sector. As one Controller stated:

- "We're increasing the amount of actions and decisions we're having to make, and everybody misses some of these things (potential conflicts) whenever you sit down and you start working...but then you keep going back around (scanning the scope) and checking what you've done and you catch it. You get so many of these things in there that you have to do...something's going to get missed..."

8.1.3 Conflicts and Route Scheduling

Although the current ATC system is oftentimes seen as being overly restrictive and highly inflexible in its structure, many believe that it is because of this structure that conflicts are avoided. For example:

- "Just about all the airplanes become a potential (conflict) when you give them any leniency (freedom)...and I thought about a couple of times giving clearances like, 'maintain present heading,' because the headings that the aircraft were on...they were going to miss each other. But because they had the ability to turn, there was a couple of places where the aircraft only had to turn 10 or 20 degrees, and now they're together (in conflict) with airplanes that they're separated from *if* they remain on their present heading."

- C1: "Aircraft speeds don't really affect the complexity that much because you're used to certain performance characteristics...I'm using the ground speeds a lot. Now, if an aircraft changes his speed...if he just all of a sudden decides he's going to speed up because he's in cruise...that can increase your complexity a lot...you could have a 30 or 40 knot overtake all of a sudden that you didn't have before."

C2: "And there are rules to protect us from that, right now."

After one simulation scenario, we asked a Controller if more detailed flight plan/intent information would help him manage traffic under some sort of free flight rules, instead of simply allowing aircraft to change heading, speed, or altitude at will. His response indicated that such detailed information might create additional problems:

- "Strategically, things can get pretty bizarre because of the way the jet stream flows....it'll do some really wild things. What's their profile look like from the ground? It may say, 'we're going to do 28 (FL280) until Denver, then we're going to climb to 37 until Omaha, and then we're going to drop back down to 26 because of the winds again until we get east of Chicago, then we're going to climb back to 39.' That's an ugly strategic profile from the get-go, and I don't want somebody doing that to me and filing a flight plan that way. But tactically, if they get up there and start changing their minds like that...I don't know."

Therefore, it is important that we prevent both the situation in which every aircraft is a possible conflict because the intent is unknown and the situation wherein the Controller is overloaded with detailed flight plan information for every single aircraft. A possible solution to this problem might be to provide the users with tools which will help them to make modifications to *both* aircraft routes *and* airspace structures so that the resulting airspace and traffic situations allow for an increased amount of aircraft flight flexibility while not overloading the Controllers' cognitive limitations with an excess of detailed information.

8.1.4 Training

In order to move towards a free flight system, there will have to be a change in the way Pilots and Controllers are trained. Current, procedural-based training may no longer be sufficient. Procedures are based on the identification and classification of existing conditions. Controllers and Pilots operating in a free flight environment will need to be able to handle an entirely new set of conditions (which are very likely to be more dynamic, and therefore not as easily identified) in order to maintain the flexibility of the new system:

- "We're Air Traffic *Controllers*. When you get into a free flight situation, you're becoming Air Traffic Monitors...except your responsibilities haven't changed, it's just what you have to do to maintain the same separation standards is now completely different. You're trying to interfere the least that you possibly can and I think as you see some other people come in here (to control the simulations)...they're not going to try to minimize their interference. Because when you say, "ensure separation," some of these people are going to come in here and they're going to **ensure** separation. They're going to take away as much of that latitude (as possible)...but that's also what we're trained for."

The relationship that currently exists between Controllers and Pilots is going to change with the advent of the new system. The details of shared responsibility for separation will be unfamiliar to both Controllers and Pilots and the mediation of conflicts between the two groups (i.e., which group retains ultimate responsibility) will no doubt be a sensitive issue that will require closer examination. As mentioned earlier, many Controllers stated that they would like to see the airlines assume more responsibility for separation violations. The acceptance of separation violation responsibility by the airlines will no doubt <u>significantly</u> affect the implementation of the future system and therefore merits additional attention.

9.1 The Complexity of Air Traffic Control

A Controller's primary task is to maintain separation. To do so, s/he must use aircraft information, information on the airspace, and any other available resources to effectively control and predict potential conflicts that jeopardize this separation. These conflicts can include conflicts between two aircraft, conflicts between aircraft paths and airspace, and conflicts between the demand and capacity of a particular airport. Air traffic control, with respect to conflict resolution, typically has four main processes: planning, implementation, monitoring, and evaluation. These processes, along with a discussion of how they are impacted by air traffic complexity, are presented below.

In the planning process, the Controller's goal is to determine the best course of action needed to resolve each traffic conflict. This process typically results in a set of re-routes, vectors, speed assignments, altitude changes, coordination with other Air Traffic Specialists, or other control actions. However, as part of this planning process, the Controller must also evaluate the impact that a given control action, which is intended to solve one particular conflict, might have on the rest of the system. Once the Controller completes the planning process and has determined the necessary control actions to be taken, the Controller implements the plan through the use of various communication and data entry tasks. Although this implementation may be viewed as only being a physical task, if the implementation itself requires some sort of planned coordination, then the distinction of whether the implementation is a physical task or a mental task is not entirely clear. After implementation, the Controller must then monitor the situation to ensure the conformance of the situation to the plan, and to evaluate the effectiveness of the plan in resolving the conflicts.

The complexity associated with these processes stems from the fact that all of the above tasks, except, perhaps, the actual implementation of the plan, rely heavily on the cognitive abilities of the Controller. Further, each of these tasks is continuously being performed for different aircraft at different times, and each of the processes may result in the initiation of another process, as shown in Figure 14.

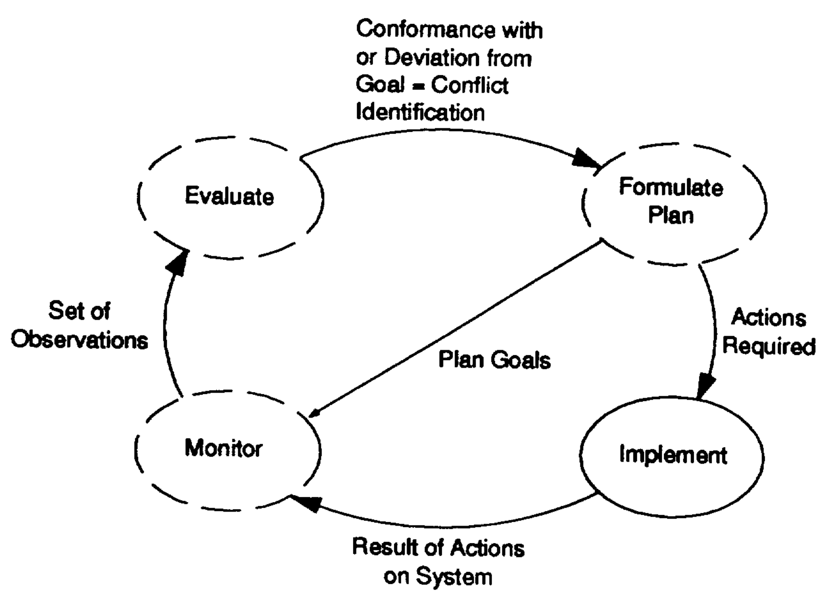

Figure 23. Mental and Physical Processes Required in Air Traffic Control

The "Implement" process is comprised of the physical actions required to carry out a specific plan. According to this diagram, this process is indicated by a solid oval and is the only externally observable process in air traffic control. The other processes, indicated with dashed ovals, are internal processes that combine to determine the level of mental effort required for air traffic control. According to the diagram above, then, the complexity of ATC is realized through the evaluation of the combination of the physical and mental tasks or processes that a Controller needs to perform.

9.2 Current Vs. Future Complexities

The complexity of air traffic control is of particular importance in the study of the free flight concept for ATC. The removal of many of the procedures that are currently used for the control of air traffic as advocated by the free flight concept will most likely affect all of the task elements (both physical and mental tasks) that must be conducted by the ATS. For example, the process of evaluating a traffic situation and determining the conflicts that will arise will most likely become more difficult for a number of different reasons. The loss of the current existing organization of traffic flows that is created through the use of non-free flight ATC procedures will potentially increase the number of possible conflicts that might occur. By assigning each aircraft to a specific route selected from a finite and relatively small set of routes, today's Controller is significantly reducing the number of locations at which aircraft may come into conflict. Additionally, when two aircraft are assigned to the same route, they are separated by altitude or by time along the route. This separation can then be easily maintained and monitored through the use of various methods, such as speed control. The Controller simply ensures that the distance between the aircraft does not decrease below that which is acceptable, by assigning speeds if necessary.

Two or more aircraft on the same route, with speeds matched to ensure separation, combine to form what is referred to as a 'stream.' By creating multiple streams of aircraft, the current ATC procedures allow the Controller to primarily focus on the intersection point of two streams, rather than having to analyze every aircraft against every other aircraft for a potential conflict. As mentioned above, separation is easily maintained and monitored through speed control, within a stream. Between streams, the particular aircraft that may conflict are easily identifiable because, based on speed, there will generally only be a few aircraft, at most, in each stream that have the potential to be involved in a conflict situation. The establishment of streams allows a simple identification of potential conflicts and further reduces the complexity (as experienced by the Controller) of the air traffic situation.

It can be argued that both the evaluation and planning tasks will become more difficult under free flight procedures because of the increased flexibility that will be afforded aircraft. Under free flight, the Controller will no longer know the <u>exact</u> route that an aircraft is expected to follow. The current RTCA definition of free flight allows aircraft the flexibility of selecting their own route, speed and altitude, with consideration for aircraft to aircraft conflicts, aircraft to airspace conflicts, capacity constraints, and safety (RTCA, 1995). Thus, a Controller will be required to consider the possible conflicts that may occur in a region around an *estimate* of the route that the aircraft will follow in the evaluation and planning process. In this case, the Controller experiences a considerable increase in the number of degrees of freedom that need to be managed.

The level of difficulty of monitoring an air traffic situation will most likely increase for a similar reason. Aircraft have the flexibility to select their own route under free flight procedures, and to change the route that they will fly at their discretion. Thus, it will be more difficult to predict the actions and intentions of aircraft. Air Traffic Specialists will have to monitor the flight path of each aircraft more closely to determine when an aircraft has decided to change course or speed.

Finally, the implementation task will most likely become less difficult under free flight. This is because free flight places much of the decision making process in the cockpit of the aircraft, unless the Controller must take action for aircraft or airspace separation assurance, or for traffic management purposes. As stated above, under free flight, aircraft will select their own route. Thus, Air Traffic Specialists will not provide route instructions, unless they have been required to take action for the previously identified reasons. However, implementation may be quite simple or very difficult, depending on the traffic structure and the goals of the aircraft.

Since humans have limited processing capabilities, and air traffic complexity impacts all of the processes described above, it is very possible that a Controller can reach his or her limit of the level of complexity that is manageable. Therefore, it would prove useful to be able to create a measure of complexity that would allow us to determine when a Controller is approaching the limits of his or her processing abilities. This measure could be used in the current ATC environment to predict and/or manage when a Controller will reach his or her processing limits. Equally important is the fact that this measure could potentially be used to help understand the impact that free flight procedures will have on the air traffic Controllers.

9.3 Previous Work

9.3.1 "Measures" of Complexity

A number of studies have already addressed the issue of the complexity of an ATC situation (for an in-depth review, see Mogford, Guttman, Morrow, and Kopardekar, 1995). In some cases, these works have focused on an analysis of the amount of physical work required of an ATS (Schmidt, 1976; Soede, Coeterier, and Stassen, 1971; Thornhill, 1995). In these studies, the goal was to use a measure of physical workload as an indication of the level of complexity of the situation under study. Data that provides an indication of the amount of time that a Controller spends performing specific, identifiable, physical tasks in the process of handling the traffic situation is collected and analyzed. Results from these types of studies suggest that an increase in the amount of time spent performing these physical tasks is the result of an increase in Controller workload; which can be considered to be the result of increased complexity.

An example of a system designed to collect this type of information is the Sector Design and Analysis Tool (SDAT) (MacLennan, 1994). The SDAT provides a measurement of Controller workload by processing System Analysis Recording (SAR) data from the FAA Host computer system. The SAR data contains all flight plan and radar track data for all aircraft that were handled in each of the sectors at an Air Route Traffic Control Center (ARTCC). In addition to this data, the SAR process records a significant amount of other system data, including all of the data entries that are made by an ATS in the process of controlling traffic. The SDAT tool then uses the number of recorded entries as an indication of the relative level of Controller workload during that period of time.

Other studies have used a measurement of the amount of time a Controller spends in communication, either with aircraft or with other Controllers, as a measurement of workload. Thornhill (1995) used the number of entries made by an ATS, the amount of time spent in communication, and other traffic-related factors to create a measure of the workload required to handle a traffic situation. Suggested applications of his work include the dynamic scheduling/staffing of Controllers based on physical workload capacity. In this case, as complexity increases, he suggests that additional Controllers may be required.

Still other studies have examined various traffic and airspace elements as a measure of complexity (Federal Aviation Administration, 1984; Stein, 1985). In these studies, numerical counts such as the number of aircraft present in a sector, the number of arrivals, or the number of departures during a specific traffic period is used as a measure of complexity. Results from these studies suggest that an increase in the amount of traffic is related to an increase in traffic complexity. Another study examined the impact that sector geometry, combined with traffic density, had on

Controller performance (Buckley, DeBaryshe, Hitchner, & Kohn, 1983). Although performance may not necessarily be directly associated with complexity, this work did uncover a strong interaction between sector geometry and traffic density that could have implications for any study examining the effects of traffic density on perceived complexity.

9.3.2 Two Types of Workload

While many factors contribute to the complexity of an air traffic control situation, the impact of this complexity on the Controller can be examined in terms of both physical and mental workload, as stated above. Throughout this paper, "physical workload" has been used to refer to the level of physical activity required by a Controller, resulting from performing tasks that are simply the interfaces of the Controller with his or her operating environment. In other words, physical workload tasks are those tasks that are measurable external actions of the Controller, used to implement a plan of action that has been previously determined. These types of tasks include the communications and data entry tasks that have been discussed above.

"Mental workload" refers to the amount of cognitive activity spent performing such tasks as the evaluating, planning, and monitoring necessary for effective air traffic control. The current study has described a method for examining the factors that impact the performance of these types of tasks (mental tasks that require significant cognitive activity), and has shown how a greater understanding of these factors may be incorporated into a measurement of complexity. Although these two definitions treat physical and mental workload separately, problem solving and resolution typically places demands on both the physical and mental capabilities of the Controller.

9.3.3 An Incomplete Picture

Although measurements such as the type and length of physical activity can be used as an indication of the complexity of an air traffic situation, many studies discount the fact that the amount of physical activity observed in a particular situation may not necessarily reflect the amount of cognitive activity required. In many of these studies, the focus has been on measuring the physical activity levels, and inferring the level of cognitive effort required. However, this inference may not necessarily be correct. Examples to support this argument are presented in the following scenarios.

Some of the procedures that are established for the control of air traffic require multiple or lengthy instructions to be communicated to every aircraft. Often, repetitive data entries may also be required. These tasks in themselves (i.e., not including the planning for these tasks) may become very familiar and automatic to the Controller and require very little cognitive activity, even though a high level of physical workload may be required. For example, in some cases the planning necessary to vector an aircraft around an SUA may require a minimal amount of cognitive activity because the Controller has performed the task multiple times in the past and is intimately familiar with the headings that will be required. However, this process may in fact require many clearances to be communicated to the aircraft, and may require a re-route to be entered into the system. Other examples of such tasks are vectoring aircraft on a standard traffic pattern, clearing an aircraft for an approach, making entries to hand an aircraft off to another sector, or entering common re-routes into the system. In this particular example, some previous studies might have identified the situation as being complex due to the high level of physical work activity (i.e., number of communications, number of data entries, etc.) required for control. Nevertheless, it is likely that the level of mental workload experienced would be relatively low.

Another example can be made of the process of turning an aircraft onto the base leg in a standard traffic pattern. While the implementation of this task requires only one brief clearance to the aircraft, the planning for this task requires the identification and creation of a slot for the aircraft on final approach, considering all other aircraft that are currently competing for such slots. This process in itself may require other planning, implementation and monitoring tasks to be performed, in order to create the needed slot. The key difference in this situation is that there is a great deal of cognitive activity involved in preparing for one short clearance. The task time and effort needed to issue a single clearance will not provide a meaningful measure of the amount of cognitive activity involved.

As mentioned before, we believe that the dependency on measuring physical activity and inferring the level of mental activity may not be the most appropriate method to understand air traffic complexity. As in the first example above, previous measures might have identified the situation as being complex due to the high level of physical activity required. However, it is likely that the complexity of the situation, viewed from a cognitive standpoint, would be considered low. Therefore, our complexity measure primarily focuses on the factors of the air traffic situation that impact a Controller's mental processes.

9.3.4 Measuring Mental Workload

Theoretically speaking, the "concept" of workload is better defined as a construct. That is, workload itself is not directly observable or measurable, but must be inferred, based on measures and observations of other elements (such as mental and physical tasks) (Mogford, et al., 1995; Stein, 1985). The selection of these elements will shape our definition and understanding of the workload being inferred.

Measurements such as the number of communications and data entries, as well as numerical counts of aircraft have been adopted primarily because this physical data is some of the only direct data that is readily available. Directly measuring the cognitive load that is being experienced is more difficult and, unfortunately, highly intrusive in a real-world, operational setting. However, if we maintain the position that simple keystrokes for data entry purposes eventually become somewhat of an automatic process, then it remains that the mental calculations and planning work required by a Controller is the far more difficult aspect of the job. Therefore, a useful measure of complexity also needs to consider the details of an air traffic situation that affect the cognitive abilities of the Controller, and not just the physical workload.

This paper does not attempt to define an exact model for measuring the cognitive functions of an ATS during control. As well, the work described in this paper was not designed to measure the amount of mental workload experienced by an ATS during problem solving (i.e., conflict detection and resolution) activities. Although an accurate mental workload measure would be very useful, and work has been done in this area, it is beyond the scope of this paper primarily because of the many problems associated with the measurement of mental workload associated with a particular task (Muckler and Seven, 1992; Wierwille and Eggemeier, 1993). Also, as stated in Charlton (1996), there is very little agreement in the scientific community as to which measures should be used to best quantify the level of mental workload experienced in a given situation.

Therefore, the work in this paper presents a framework and an approach for measuring and evaluating the *perceived* complexity of an air traffic situation, with an emphasis on the traffic characteristics that impact the cognitive activity of the Controller. Since we are dealing with the perceived complexity involved in an air traffic situation, we are required to communicate with as many Air Traffic Specialists as possible in order to get a proper sampling of their perceptions, and a better understanding of the complexity associated with their jobs.

10.0 CONCLUSIONS

The complexity of an air traffic situation can not be completely captured by only using the number of communications and data entries made while controlling traffic. The processes and tasks involved in the control of air traffic are highly cognitive tasks and it is not necessarily true that the observable implementation (physical actions) of the results of these cognitive tasks provides a good correlation with the complexity of the cognitive processes themselves. Therefore, to better understand the complexity of an air traffic situation, we need to consider the cognitive tasks required of the Controller--the planning, monitoring, and evaluating tasks.

The study presented herein was aimed at evaluating the characteristics of an air traffic situation that impact the cognitive abilities of the Controller. This initial study has provided many insights into the Controller's perception of Air Traffic Control complexity. Although we believe we have a useable, initial model of this perception of complexity, it is important to further develop the algorithm to incorporate the impact of such issues as communication and coordination, Special Use Airspace, and weather.

Further developments of the complexity measure will also need to address a number of other issues. For example, the simulation environment only examined one sector in Denver ARTCC airspace. In order to be able to fully validate the measure, we need to evaluate it in a number of other sectors and a number of other ARTCC facilities. The relationships between the factors in the measure also need further review. Since we only used Controllers from Denver ARTCC, one might be justified in saying that the measure is only useful in that particular facility. Indeed, it would not be surprising if Controllers from the facilities in Washington (ZDC) or New York (ZNY) have somewhat of a different view of how the individual factors contribute to the overall complexity of Air Traffic Control. Having an increased number of Controllers, from different areas of the country would allow us a more complete understanding of how a valid measure of ATC complexity should be computed.

The information gained from a validated measurement of the complexity of a Controller's task can be very useful in many aspects of air traffic management, planning, and the development of new procedures. This measurement will prove even more useful if it can be used in a predictive manner. Such a measurement/prediction will allow traffic management decisions to be made with consideration for the impact they will have on individual Controllers and sectors. As well, this measurement could also be useful for understanding the impact that proposed procedural changes will have on the Controller and the ATC system. Finally, a complexity prediction capability could also be incorporated in the development of new ATC automation tools, so that the suggestions and advisories generated by the tools would be required to consider the resulting complexity of the air traffic situation.

It is important to note that in the Previous Work section of this paper, much of the discussion focused on what we believe to be the limitations of prior studies. While these limitations were detailed to emphasize the need for the experiment conducted for this report, it must be stated that this current study was designed to build upon these previous findings. Part of our long-term goals, which will integrate information from the current study, is to develop a system that takes some of the complexity out of the coordination problem, thereby leaving Controllers with more time (and resources) to focus on the complexity of the traffic situation at hand.

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12.0 APPENDICES

APPENDIX A - DATA SHEETS

Critical Decision Interview Questions

1. ARTCC: ______________

2. Region

   N NE E SE S SW W NW

3. Sector Number? ______________

4. High or Low Sector? ______________

5. Sector Type? Departure Arrival Mix

6. Please draw the scenario on the map provided, including the shape of the sector, as best you can recall. Include any special use airspace or weather cells that were present at the time.

7. Please describe the situation as best you can recall:

FOR EACH DECISION POINT:

What were your cues for action at this time? What information did you use in making this particular decision?

8. Were you reminded of any previous experiences at this time? What about the two situations was the same? Did you use any information in the previous experience to help in your current decision?

9. What were your *specific* goals at this time?

10. How did you resolve the situation? Please describe the strategy you used in detail.

11. Did you consider other alternatives? What were they? Why did you choose not to go with those?

12. What specific events happened that may have contributed to this particular situation being so complex?

13. What information was absolutely necessary in being able to handle this situation? What type of training or experience was necessary or helpful to make this decision?

14. What **one** thing made this situation so complex? If this were different, how might you have handled the situation?

15. What **combination of things** collectively made the situation complex?

16. How much did the fact that you had limited time to deal with the situation affect your perception of the overall complexity?

17. How do you think you would have handled this situation at an earlier/later point in your career?

Complexity Focus Group - Briefing

Overview

This study is designed to help us identify potential factors (i.e., traffic characteristics, weather patterns, etc.) that affect your perception of the complexity of your job. In the current study, these complexity factors will be used to develop a model of the level of complexity associated with handling an air traffic situation. Our goal is to be able to understand the complexity of an air traffic control situation under the currently available technologies/procedures. In the future, this model will then be used in an experiment to determine if it is feasible to *predict* the complexity of an air traffic control situation.

Mental Versus Physical Workload

Many studies in the past have used the level of physical workload (number and/or length of communications, number of keyboard entries, etc.) as an indicator of the level of "complexity" involved in Air Traffic Control. However, in many instances an air traffic situation requires an extensive amount of mental thought and calculation, with only 1 or 2 keyboard entries needed for execution. Given this assumption, we believe that it is more important for us to understand the factors that affect how much thinking and planning associated with air traffic control. Rather than attempt to recreate previous studies using a measurement of physical task time and/or frequency, we would like to investigate the cognitive aspect of ATC complexity. Therefore, the approach taken in this modeling effort involves the identification and prediction of specific traffic and environmental characteristics that impact your evaluation, planning and monitoring--the tasks that increase your mental workload. The future model will be based on trajectory predictions for each aircraft in a traffic scenario, as well as other factors related to the airspace environment: basic density of aircraft, known intentions of aircraft, weather factors, and delay requirements due to downstream capacity constraints. In general, we will attempt to model any identifiable factor that impacts or adds to the difficulty of the evaluation, planning or monitoring tasks in air traffic control.

Complexity Factor Identification

Again, the reason we need to include you in this study is because of the amount of detailed knowledge you have about controlling traffic. As we mentioned above, many previous studies have examined the complexity of air traffic control through the amount or number of physical actions taken, which are easily measured. However, we are trying to understand the cognitive aspects of ATC, which are very difficult to measure. Working with you, we hope to gain a better understanding of this side of ATC.

We understand that many of the factors that we have defined below are going to be difficult to measure. Therefore, we are also going to ask you about traffic scenarios that you remember to be highly complex due to the factors that you have identified. We will be working with you to help us better understand the impact these factors have on the perceived complexity of control, through an evaluation of these traffic scenarios. Also, we will try to understand how to best measure these factors so that we can collect the information needed.

Detailed Factor Interview Form

For each of the complexity factors listed below, we need to be able to determine if there are specific "levels" of complexity within each factor. If so, we need to understand which "level" of that factor creates the most complexity, which creates some complexity, and which creates only a little complexity. After this question and answer session, we will ask you to fill out a form which has you rank the various complexity measures according to the impact you feel they have on complexity.

Airspace Structure (STR)

This measurement will examine the impact that sector size and structure has on the complexity of air traffic control.

Please describe the shape and size characteristics of a sector that might be a particularly difficult sector for control. For example, is a narrow, long sector more complex for control than a large, fairly round sector?

Why?

How many different levels makes sense with respect to sector shapes? For example, would it make sense for us to compare two different sector shapes (such as narrow vs. wide)? More?

With respect to the traffic in the sector, how does the complexity change with traffic that is moving against the structure of the sector? For example, in a narrow, long sector, how does the presence of crossing traffic affect the complexity of control for that sector?

Special Use Airspace (SUA)

This measure is intended to identify how the number/size/activity of restricted areas, warning areas, and military airspace impact the complexity of an air traffic scenario. Basically, what it is about SUAs that have the potential to increase the complexity of control.

Is it simply that they are active?

Does it have anything to do with their location within the sector? If so, where in the sector does an SUA cause higher complexity? Where does it not contribute very much to the complexity?

Does the size of the SUAs affect the complexity?

How does the combination of activity level/location/size impact complexity?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Weather Effects On Airspace Structure (WST)

Weather impacts the amount of usable airspace, and therefore the structure (size and shape) of the sector. This measure will examine the impact that a weather cell can have on the structure of a sector, and how that translates into increased complexity.

Is complexity (due to the reduced size and changed shape) increased when a weather cell is present?

Does it have anything to do with its location within the sector? If so, where in the sector does a weather cell cause higher complexity? Where does it not contribute very much to the complexity?

Do larger weather cells make traffic control more complex?

How does the combination of number of weather cells, their location within the sector, and their size impact complexity?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Proximity of Potential Conflicts to Sector Boundary (PRX)

This measure is an examination of the location(s) of the potential conflict(s) with respect to current sector boundaries.

Would you say that conflict locations that are closer to sector boundaries result in a higher level of complexity?

Is there a range of distance to the boundary (e.g., 10 miles) that results in high complexity? For example, is complexity higher when the conflict is 5 miles from the boundary? Not as high 6-20 miles, and even less high 21-50 miles?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Aircraft Density (DNS)

A measurement of the density of aircraft with respect to the usable amount of airspace.

Would you say that increased aircraft density results in increased complexity?

Is there some sort of guideline that we can use to assign different weights to different levels of aircraft density?

What is considered high density? Some # of aircraft per hour?

If so, what range or number of aircraft is considered very high density? High density? Low density?

Very High ________

High ________

Low ________

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Number of Facilities (FAC)

A simple count of the number of facilities being served by, or contained within, the sector.

Our assumption is that an increase in the number of facilities corresponds to an increase in the complexity of control. Is this a valid assumption to make?

What is considered the number of facilities that significantly increase complexity? (i.e., two facilities? Three or more?)

Number of Aircraft Climbing or Descending (CoD)

A simple numerical count of the number of aircraft expected to climb or descend in altitude. Our assumption is that if many aircraft are climbing or descending within a sector, then this could potentially result in a more complex scenario.

Is this a valid assumption to make?

Is there some sort of guideline that we can use to assign different weights to different levels of the number of aircraft climbing or descending?

What is considered a high number of ACFT climbing or descending? Perhaps some % of the # of aircraft within the sector?

Very High ________

High ________

Low ________

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Number of Crossing Altitude Profiles (CAP)

This measure is an examination of the number of ascending and descending aircraft profile pairs that are expected to occupy (in crossing) the same altitude within a specified period of time in the future. Our assumption is that if many aircraft pairs are expected to have crossing profiles, then this could potentially result in a more complex scenario.

Is this a valid assumption to make?

Can the levels of this factor be determined with a certain percentage or number of aircraft pairs that are expected to occupy the same altitude (crossing profiles)?

If so, what are the breakdowns of these percentages?

Very High _________

High _________

Low _________

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Weather Effects On Aircraft Density (WDN)
Weather also impacts the density of the aircraft in the sector, because the amount of available airspace is reduced. Therefore, this measure will examine the impact that a weather cell has on the density of aircraft.

Is complexity due to density increased when a weather cell is present? (i.e., a weather cell reduces the amount of available airspace and therefore, the same number of aircraft will be considered to be a higher level of density.)

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Variance in Aircraft Speed (VAS)
A measurement that looks at the variability of speed tracked for each aircraft.

We are assuming that if all of the aircraft are going the same speed (e.g., 250 KIAS in lower ARTCC sectors), then it might be easier to deal with because you don't have to worry about the mix of speeds that need to be managed. Is this a valid assumption?

Is there a range of speeds that you consider to be generally the same? For example, the difference between 220 and 230 KIAS might not be that great, but the difference between 180 and 230 KIAS might be considerable to affect the complexity of the scenario.

Is this range the same at high and low speeds?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Variance in Directions of Flight (VDF)
A measurement that looks at the variability of direction for each aircraft to be controlled.

We are assuming that if all of the aircraft are going in the same general direction (or perhaps are at least in streams), then it might be easier to deal with because you don't have to deal with many aircraft going in many different directions (as you would, for example, if you were just going into or coming out of a holding situation). Is this a valid assumption?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Performance Mix of Traffic (PRF)
A measurement that looks at the variance in performance capabilities of current and expected aircraft.

We are assuming that if all of the aircraft have relatively the same performance characteristics, then it might be easier to deal with because you don't have to remember that there is a mix of characteristics that need to be managed. Is this a valid assumption?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Winds (WND)
A measure of the wind speed and azimuth by altitude, and its impact on aircraft performance characteristics.

In general, what level of wind speed starts to somewhat impact aircraft performance?

In general, what level of wind speed starts to significantly impact aircraft performance?

Which is most difficult to deal with? Tailwinds, headwinds, or crosswinds? Our assumption would be crosswinds due to the impact they have on turn ratios. Is this a correct assumption?

Distribution of Closest Points of Approach (CPA)
This measure is a time-based distribution of the number of intersecting (laterally) flight paths which could be potential conflicts. What we're trying to get at in this case is to determine what the expected separation distance has to be before you feel that you should do something about two potentially conflicting aircraft.

For example, if two aircraft look like they're going to cross within 5 miles of each other, you obviously take some sort of action to prevent that occurrence. However, if it looks like two aircraft are going to cross within 8 miles of each other, do you still take some action? What is the approximate limit for which you will take action?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Angle of Convergence in Conflict Situation (ANG)
A measure that examines the predicted angle of convergence in a conflict. Shallower angles of convergence result in a longer period of potential conflict, so we are assuming that this might result in a higher level of complexity.

Is this a valid assumption?

Is there a specific angle (or angles) that could be considered a cutoff point(s) for different levels of complexity? For example: 1° - 30° angle of convergence could be very high complexity, 31° - 60° is high complexity and 61° - 90° is low complexity

Very High	________
High	________
Low	________

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Neighbors (NBR)
The proximity in lat. and vert. distance between aircraft pairs in conflict and other aircraft within some parameter distance or time.

Is it meaningful to simply say that the presence of neighboring aircraft impacts perceived complexity?

How close do these neighbors have to be in order for them to impact the complexity? Are there varying levels of distance that could be assigned different weights with respect to how they impact complexity? For example, if a neighbor is within 8 miles laterally, could this make the complexity very high?

Lateral Distance		Vertical Distance	
Very High	________	Very High	________
High	________	High	________
Low	________	Low	________

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Level of Knowledge of Intent of Aircraft (INT)
A measure that looks at the effects that the knowledge of intent of an aircraft has on the complexity of a conflict involving that aircraft.

Here, we are assuming that if you don't have the knowledge of intent of an aircraft, the complexity is increased. Is this a reasonable assumption to make?

Separation Requirements (SEP)
A measure that examines the impact that imposed separation requirements for longitudinal sequencing and spacing has on complexity.

One assumption is that under **special** separation requirements (e.g., miles in trail restrictions, etc.) the complexity could increase. Is this a reasonable assumption to make?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Coordination (CRD)
The impact that the presence of aircraft that require some form of coordination (with other sectors, etc.) for proper control has on the complexity of an air traffic situation.

For this factor, we are assuming that, in general, the fact that you have to do some coordination for a specific aircraft increases the complexity of the scenario. Is this a valid assumption to make?

What would be an appropriate time window to examine for this measure (i.e., how far into the future would it make sense to predict the impact of this factor on the expected complexity)?

_____ minutes

Factor Ratings and Weightings

Overview

The purpose of this questionnaire is to help us understand the relative and absolute levels of importance that you place on each of the complexity factors. What we would like for you to do is to review the list of complexity factors (and the descriptions of each) that we have compiled, and to rate the factors in two ways. First, we would like you to rate each factor based on how strongly you feel that factor contributes to the complexity of an air traffic situation.

For the first section of this questionnaire, we ask that you consider each factor independently of each other. We realize that some of the factors presented are closely related in terms of their definitions and their impact on the perceived complexity of an air traffic situation, and therefore will be difficult to rate independently. However, we will address the relationships between factors in the second section of this questionnaire. In the second section, you will be asked to rate the absolute levels of complexity for each *pair* of identified complexity factors.

Finally, for the last part of this questionnaire, we would like you to rate the **relative** contribution of each of the (single) listed factors. Although this will also be a difficult task, we ask that you please rate all of the factors from 1 to xx. It might be helpful to use a pencil, in case you change one of your decisions.

For all of the ratings given in this questionnaire, you are free to go back and change your decision at any time.

After you are finished with these questionnaires, we will work with you to try to define the details of when and how these factors affect the complexity of your job, based on previous situations that you have encountered.

Section 1 - Absolute Levels of Complexity

For the first part of this questionnaire, we would like you to rate each complexity factor from 1 to 10, based on how strongly you feel that factor contributes to the overall complexity of an air traffic situation. For example, you should assign a rating of "10" to any factor that you feel greatly impacts the level of complexity you experience when controlling an air traffic situation. Conversely, you should assign a rating of "1" to any factor that you feel has very little impact on the complexity of a situation. A rating of "5" should be given to a factor which you feel only somewhat impacts the overall complexity of a situation. Finally, assign a rating of "0" to any factor that you feel has nothing to do with the complexity of air traffic control.

In the second section, we are also going to ask you to rate the different **combinations** of pairs of factors in the same manner as above. In this case, we would like you to assign a rating of "10" to a pair of factors that you feel, when combined, greatly impact the complexity of air traffic control, and to assign a rating of "1" to a pair of factors that you feel do not have much impact on the complexity. Please continue with each set of factor pairs in the same manner as before.

The complexity factors used for this questionnaire are listed on the accompanying page. The same acronyms will be used throughout the entire questionnaire. Please feel free to refer to them as often as needed. In addition, we will be happy to answer any questions you have at any time.

Single Factor, Absolute Ratings

(STR)	10	9	8	7	6	5	4	3	2	1	0
(SUA)	10	9	8	7	6	5	4	3	2	1	0
(WST)	10	9	8	7	6	5	4	3	2	1	0
(PRX)	10	9	8	7	6	5	4	3	2	1	0
(DNS)	10	9	8	7	6	5	4	3	2	1	0
(FAC)	10	9	8	7	6	5	4	3	2	1	0
(CoD)	10	9	8	7	6	5	4	3	2	1	0
(CAP)	10	9	8	7	6	5	4	3	2	1	0
(WDN)	10	9	8	7	6	5	4	3	2	1	0
(VAS)	10	9	8	7	6	5	4	3	2	1	0
(VDF)	10	9	8	7	6	5	4	3	2	1	0
(PRF)	10	9	8	7	6	5	4	3	2	1	0
(WND)	10	9	8	7	6	5	4	3	2	1	0
(CPA)	10	9	8	7	6	5	4	3	2	1	0
(ANG)	10	9	8	7	6	5	4	3	2	1	0
(NBR)	10	9	8	7	6	5	4	3	2	1	0
(INT)	10	9	8	7	6	5	4	3	2	1	0
(SEP)	10	9	8	7	6	5	4	3	2	1	0
(CRD)	10	9	8	7	6	5	4	3	2	1	0

Section 2 - Absolute Levels of Complexity for Factor Pairs

For the next section of this questionnaire, we ask that you rate each *factor* pair in the same manner as you did for the individual factors. That is, rate each factor pair based on how strongly you feel those two factors, when experienced at the same time, contribute to the complexity of an air traffic situation. Again, as an example, you should assign a rating of "10" to any pair of factors that, when combined, you feel <u>greatly</u> impact the level of complexity you experience when controlling an air traffic situation. Conversely, you should assign a rating of "1" to any pair of factors that you feel have <u>very little</u> impact on the complexity of a situation. A rating of "5" should be given a pair of factors which you feel only <u>somewhat</u> impact the overall complexity of a situation. Finally, if appropriate, assign a rating of "0" to any pair of factors that you feel have nothing to do with the complexity of air traffic control.

The acronyms used in the table are the same as before, and you may refer to them at any time. Please write in the number (0 -10) in each space corresponding with the factor pair being rated.

	STR	SUA	WST	PRX	DNS	FAC	CoD	CAP	WDN	VAS	VDF	PRF	WND	CPA	ANG	NBR	INT	SEP	CRD
STR																			
SUA																			
WST																			
PRX																			
DNS																			
FAC																			
CoD																			
CAP																			
WDN																			
VAS																			
VDF																			
PRF																			
WND																			
CPA																			
ANG																			
NBR																			
INT																			
SEP																			
CRD																			

Section 3 - Relative Levels of Complexity

For the final section of this questionnaire, we would like you to rate the **relative** contribution of each of the listed factors, against all the others. For example, the factor that you feel has the greatest impact on the complexity of an air traffic situation (above all other listed factors) should be given the rating of "1." The factor that has the second greatest impact on the complexity (above all other remaining factors) should be given the rating of "2." Although this is a difficult task, given the number of factors involved, please continue rating all of the factors from 1 to xx. It might be helpful to use a pencil, in case you change one of your decisions.

Single Factors, Relative Weightings

(STR)	
(SUA)	
(WST)	
(PRX)	
(DNS)	
(FAC)	
(CoD)	
(CAP)	
(WDN)	
(VAS)	
(VDF)	
(PRF)	
(WND)	
(CPA)	
(ANG)	
(NBR)	
(INT)	
(SEP)	
(CRD)	

Simulation Briefing

Overview

As previously described to you, the focus of this study is to be able to measure the different factors that affect your perception of the complexity of your job. We have developed a model of the level of complexity associated with handling an air traffic situation, based on the information you gave us when you last visited Wyndemere. The simulation sessions being held today will be used to validate our model. For these sessions, we ask that you participate in a number of simulation scenarios and to evaluate the complexity of those scenarios. We will ask you to rate both the overall complexity of the scenario, and the complexity of the scenario based on individual complexity factors. In addition, we will ask you to describe the specific complexities of the scenario, and ask for your comments on our computed complexity values.

Each of you will control a total of seven (6) scenarios. The first scenario will be a calibration scenario. This scenario will be presented to familiarize you with the simulation environment--including the communications system and the design of the sector. You do not need to fill out any questionnaires after these this scenario.

After a short break, we will present you with the five (5) test scenarios. For these test scenarios, one of you will assume the role of a Radar Controller, and one of you will simply monitor the traffic situation (Radar Monitor). The test scenarios will last about 20 minutes each. After each test scenario, you will both be given a questionnaire to complete, and will be asked to participate in a short discussion about the scenario. This discussion will be audiotaped so that we may review your comments later, when we are analyzing the data. In total, each test case (simulation scenario, complexity rating questionnaire, and discussion) will last approximately 30 minutes.

After the Radar Controller has completed all five (5) test scenarios, the Radar Controller and the Radar Monitor will switch positions--the person who was the Radar Monitor in the morning sessions will now become the Radar Controller. The simulations will proceed as above. The new Radar Controller will first be presented with the calibration scenario, and then proceed to complete the five (5) test scenarios.

There are three conditions under which the simulations will operate. For the sake of convention, these three conditions are referred to as: Current Procedures, Half Free Flight Procedures, and Full Free Flight Procedures. A description of each of these conditions is presented below.

Conditions

<u>(C)urrent Procedures</u>. In an attempt to simulate current ATC procedures, you will be presented with aircraft flying on preferred routes, and will be given full flight strips for all aircraft. For this condition, aircraft are required to request ATC clearances for any desired routing changes.

<u>(H)alf Free Flight Procedures</u>. To simulate the "Half Free Flight" portion of the simulations, aircraft will be flying direct routes between the origination and destination airports. We are going to change your short-term intent knowledge by allowing aircraft to vary their heading within a 20 mile (10 miles to each side of their "direct" flight plan) "corridor," and their altitude by 500 feet in either direction of their assigned altitude, without requiring clearance. The aircraft are still required to ask for clearance for such actions as turbulence avoidance, which would most likely change their altitude by more than 500 feet.

In addition, you will be presented with slightly modified flight strips, intended again to affect the knowledge of intent of each aircraft. Since aircraft are presented as flying along direct flight routes, you will be presented with departure and arrival airport identifiers. As well, you will be given the assigned altitude and current speed for each aircraft being controlled.

<u>(F)ull Free Flight</u>. The Full Free Flight condition will present you with aircraft flying along direct flight routes, but in this case, the aircraft are allowed to change heading and/or altitude as desired,

without necessarily requiring clearance. For this condition, the only intent information given to you is the origin and destination airports, presented on flight strips.

Complexity Factors

The table below contains a listing and a description of the complexity factors that we are measuring in these simulations.

Knowledge of Intent of Aircraft (INT)	A measure that looks at the effects that the knowledge of intent of an aircraft has on the complexity of a conflict involving that aircraft.
Aircraft Density (DNS)	A measurement of the density of aircraft with respect to the usable amount of airspace.
Aircraft Count (ACT)	A simple count of the number of aircraft that need to be controlled.
Number of Crossing Altitude Profiles (CAP)	This measure is an examination of the number of ascending and descending aircraft profile *pairs* that are expected to occupy (in crossing) the same altitude within a specified period of time in the future.
Number of Aircraft Climbing or Descending (CoD)	A simple numerical count of the number of aircraft expected to climb or descend in altitude.
Conflict Neighbors (NBR)	The proximity in lat. and vert. distance between ACFT pairs in conflict and other ACFT within some parameter distance or time.
Distribution of Closest Points of Approach (CPA)	This measure is a time-based distribution of the number of intersecting (laterally) flight paths which could be potential conflicts.
Angle of Convergence in Conflict Situation (ANG)	A measure that examines the predicted angle of convergence in a conflict. Shallower angles of convergence result in a longer period of potential conflict.
Proximity of Aircraft to Sector Boundary (PRX)	The impact that the location(s) of the aircraft with respect to current sector boundaries has on the complexity of control.
Proximity of Conflict Aircraft to Sector Boundary (PRX-C)	An examination of the location(s) of the potential conflict(s) with respect to current sector boundaries.
Performance Mix of Traffic (PRF)	A measurement that looks at the variance in performance capabilities of current and expected aircraft.
Variance in Aircraft Speed (VAS)	A measurement that looks at the variability of speed tracked for each aircraft.
Variance in Directions of Flight (VDF)	A measurement that looks at the variability of direction for each aircraft to be controlled.
Special Use Airspace (SUA)	This measure is intended to identify how the number/size/activity of restricted areas, warning areas, and military airspace impact the complexity of an air traffic scenario.
Airspace Structure (STR)	This measurement will examine the impact that sector structure has on the complexity of air traffic control.

Overall	The overall level of complexity of the scenario, across all factors.

Complexity Simulation Ratings

Please rate each complexity factor from 1 to 10, based on how strongly you feel that factor contributed to the complexity of the scenario. You should assign a rating of "10" to any factor that you feel greatly impacted the level of complexity you experienced, and a rating of "1" to any factor that you feel had very little impact on the complexity of the situation. A rating of "5" should be given to a factor which you feel only somewhat impacted the complexity. Finally, assign a rating of "0" to any factor that you feel had nothing to do with the complexity of the situation.

After you have rated each individual factor, please rate the overall complexity (again, on a scale from 1 to 10) of the scenario.

Knowledge of Intent of Aircraft	INT	10	9	8	7	6	5	4	3	2	1	0
Aircraft Density	DNS	10	9	8	7	6	5	4	3	2	1	0
Aircraft Count	ACT	10	9	8	7	6	5	4	3	2	1	0
Number of Crossing Altitude Profiles	CAP	10	9	8	7	6	5	4	3	2	1	0
Number of Aircraft Climbing or Descending	CoD	10	9	8	7	6	5	4	3	2	1	0
Conflict Neighbors	NBR	10	9	8	7	6	5	4	3	2	1	0
Distribution of Closest Points of Approach	CPA	10	9	8	7	6	5	4	3	2	1	0
Angle of Convergence in Conflict Situation	ANG	10	9	8	7	6	5	4	3	2	1	0
Proximity of Aircraft to Sector Boundary	PRX	10	9	8	7	6	5	4	3	2	1	0
Proximity of Conflict Aircraft to Boundary	PRX-C	10	9	8	7	6	5	4	3	2	1	0
Performance Mix of Traffic	PRF	10	9	8	7	6	5	4	3	2	1	0
Variance in Aircraft Speed	VAS	10	9	8	7	6	5	4	3	2	1	0
Variance in Directions of Flight	VDF	10	9	8	7	6	5	4	3	2	1	0
Special Use Airspace	SUA	10	9	8	7	6	5	4	3	2	1	0
Airspace Structure	STR	10	9	8	7	6	5	4	3	2	1	0

Overall Complexity	10	9	8	7	6	5	4	3	2	1	0

Appendix B - Complexity Focus Group Data

Introduction

The data from the absolute factor (and factor pair) ratings, the relative rankings, and the focus group interviews is presented below. As part of our study, we asked controllers to consider the impact that weather has on the complexity of control. However, since we do not have reliable weather information to include in our simulations, we are not going to measure the impact of weather in this current phase of research. Therefore, in the data table of sorted absolute ratings, presented below (on the left), the weather data has been removed. For the relative rankings of the complexity factors, presented below sorted by Z scores, the weather data remains in the table due to the fact that if weather was not considered in the original rankings, the relative relationships between the other factors may have been different. The relative importance of weather, as shown in the table, however, will not be discussed.

Absolute		
Factor	μ	$\sigma^{(n-1)}$
INT	7.9	2.18
DNS	7.2	2.39
CAP	7.2	2.04
NBR	6.7	2.11
CRD	6.7	2.45
CPA	6.5	1.78
CoD	6.4	2.07
SEP	6.3	1.70
PRX	6.0	1.94
ANG	6.0	1.89
STR	5.2	2.66
VDF	5.1	2.13
PRF	5.1	2.51
FAC	5.0	2.49
VAS	4.3	2.31
SUA	3.9	2.02
WND	3.2	1.75

Relative	
Factor	z Score
WDN	1.14
WST	1.01
INT	0.64
DNS	0.57
CoD	0.46
CPA	0.41
CAP	0.23
PRX	0.16
ANG	0.12
CRD	-0.14
NBR	-0.18
SEP	-0.21
VDF	-0.28
STR	-0.37
PRF	-0.41
SUA	-0.60
FAC	-0.68
VAS	-0.75
WND	-1.12

In the following pages, each factor will be examined according to its placement in the relative ranking scale, excepting the weather information. For each factor, a short summary of the qualitative interview data will be given, and information regarding its relative importance to complexity as well as an approximation of a weighting will be described. When possible and meaningful, information regarding the amount of time required to predict the impact of that factor on complexity will also be given.

In general, the specific absolute weightings of each complexity factor correspond (with respect to position) to the relative rankings (as shown above in the two tables). However, it was obvious in our analyses that some factors had the potential to be greatly influenced by the presence of other factors. Therefore, in the discussion of each individual factor, the tables showing the **absolute ratings of combined factors** will also be presented. In these tables, any combined factor rating of an absolute complexity above 7.0/10.0 will be presented in bold face and briefly described.

In addition, to determine how the individual factor weightings should change with the presence of an additional, influencing factor, we decided to examine the difference between the absolute ratings given for each individual factor and the absolute ratings given to that factor combined with every other factor. Statistical t-tests were performed on each distribution (i.e., [CAP] vs. [CAP x STR], [CAP] vs. [CAP x SUA], etc.), assuming equal variances. For statistically significant results (i.e., the two distributions were found to be significantly different), the t-test results will be presented and discussed. In addition, possible reasons for why a significant difference was found, and the implications that the finding has on the measurement of complexity will be given. An example describing this process is given below:

Single Factor Ratings

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	μ	$\sigma^{(n-1)}$
CAP	8	8	9	6	3	9	7	6	10	6	7.2	2.044

Factor Combination Ratings

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	μ	$\sigma^{(n-1)}$
CAP x STR	5	8	9	6	5	3	7	7	5	1	5.6	2.3664
CAP x SUA	3	6	9	2	5	4	9	4	5	1	4.8	2.6583
CAP x PRX	8	9	10	8	6	3	9	6	5	9	7.3	2.2136

In this example, statistical analyses revealed a significant difference between the absolute ratings assigned for [CAP] and the absolute ratings assigned for [CAP x SUA] ($t = 2.26$; $p < 0.037$, two-tailed). However, we see that the absolute rating of complexity associated with the combination of these two factors is significantly lower than the absolute rating of complexity assigned to the individual factor [CAP] alone. A possible reason for this might be explained by the fact that SUAs are usually not located in the direct path of a portion of airspace. If this should happen, however, the controller might opt to have, for example, all climbing aircraft to go around the north side of the SUA, and all descending aircraft go around the south side of the SUA. Therefore, the complexity of that scenario would not be considered as great an impact on complexity as the presence of a large number of crossing altitude profiles between two aircraft.

However, an interesting problem is highlighted through the examination of this example. From an intuitive standpoint, it would make sense to see an *increase* in absolute complexity, when in the presence of aircraft with crossing altitude profiles [CAP] *and* the presence of a Special Use Airspace [SUA] simply because of the fact that more aircraft route changes would be required. However, the fact that there was a significant *decrease* in this rating leads us to believe that the participants may not have all been using the same criteria for assigning factor weightings. It became apparent to us that in comparing the quantitative, numerical data for the combined ratings with the qualitative, interview data, the controllers may have inadvertently assigned a ranking based on an assumed (but unknown to us) relationship between those two factors.

This fact is further evidenced upon examination of a simple correlation matrix between individual factor, absolute ratings. In many cases, the correlations obtained do not provide any reliable correspondence to the combined factor ratings. Although no statistical tests were run to investigate this phenomenon, a cursory examination of the data does indicate that controllers may have assumed the existence of additional relationships between factors when assigning the combined rankings. Thus, in identifying weightings for combined factors, we decided to use the more detailed, but difficult to quantify, interview data as a basis for our assignments. Due to the nature of the interview data, we realize that a certain level of researcher subjectivity can impact the assigned weightings. However, since this study is designed to allow us to further modify our weightings based on simulation results, we feel that this is an acceptable step in defining and measuring complexity.

Level of Knowledge of Intent of Aircraft [INT]

Absolute Rating: 7.9

A "measure" that looks at the effects that the knowledge of intent of an aircraft has on the complexity of a conflict involving that aircraft.

During the complexity focus group interviews, the discussions about aircraft intent information were very interesting. Every controller felt that if s/he did not have aircraft intent information (with respect to changes in speeds, altitudes, headings, etc.) then the complexity would become very high. In one controller's opinion, control would become "infinitely harder". In general, it is believed that controllers may have a difficult time imagining a situation wherein they would not have short-term (i.e., 10 - 15 minutes) aircraft intent information, except, perhaps, for emergency conditions.

Therefore, during the "Free flight" portion of the simulations, we will affect the short-term intent knowledge of controllers by allowing aircraft to vary their heading within a 20 mile (10 miles to each side of their "direct" flight plan) "corridor." As well, the aircraft will also be allowed to change their altitude by 500 feet in either direction of their assigned altitude. In allowing this, we believe these actions will significantly impact the complexity of control based on the lack of short-term intent information, which is in accordance with the amount of importance they place on the knowledge of intent for control.

Combining the impact of intent information with the other factors, the average data is presented below. The high level of complexity associated with intent information combined with the proximity to sector boundaries [PRX], the variance in direction of flight [VDF], the presence of neighboring aircraft [NBR], the number of crossing altitude pairs [CAP], the closest point of approach [CAP], the performance mix of traffic [PRF], the separation requirements [SEP], the number of aircraft climbing or descending [CoD], and the angle of approach [ANG] is easily seen in this table, and will be accounted for in our complexity measure.

PRX	8.2	1.93
VDF	8	1.83
NBR	8	3.09
DNS	7.9	2.33
CAP	7.8	1.48
CPA	7.5	3.03
PRF	7.3	1.89
SEP	7.2	3.05
CoD	7.1	1.60
ANG	7.1	3.03
VAS	6.9	1.97
SUA	6.2	3.68
CRD	6.2	3.33
WND	6	3.83
STR	5.9	3.35
FAC	5.6	3.57

The reason why we do not see a significant increase in the absolute level of complexity for any of the combined factor pairs above the level of complexity assigned to the individual factor [INT] alone is due to the fact that the individual factor already has a fairly high absolute rating of complexity. This is another reason why the statistical data may not be entirely suitable or meaningful for assigning factor weightings.

Aircraft Density [DNS]

Absolute Rating: 7.2

A measurement of the density of aircraft with respect to the usable amount of airspace.

In general, all controllers stated that an increase in the density of aircraft within a specific amount of airspace results in an increase in the complexity (or potential complexity) of a situation. The reason the potential complexity is emphasized is because controllers stated that the complexity due to density also depends on what the aircraft are doing at the time. For example, if all the aircraft are simply flying through the sector in the same general direction, without needing many route changes, altitude changes, etc., then even "high" amounts of density are not really difficult to handle. However, if in that traffic situation, a number of confliction points are present, then the complexity is going to be greatly increased. As well, the complexity associated with the combination of density and PRX, CoD, INT, CAP, NBR, CRD, STR, and SUA is shown in the table below.

When asked to define "low", "medium", and "high" density, the controllers raised a number of issues. In addition to the behavior of the aircraft is the fact that the density in a sector is relative to both the size of the sector and the design of the sector (such as with arrival sectors). When asked to think in more abstract, general terms, most controllers stated that anything above 15-18 aircraft would definitely increase the complexity of the situation. The upper limit to what a controller can deal with is somewhere around 30 - 35 aircraft.

Some controllers would like to know about a significant increase in aircraft density at least 15 - 20 minutes ahead of time.

PRX	8	1.41
CoD	8	2.36
INT	7.9	2.33
CAP	7.6	1.96
NBR	7.4	2.80
CRD	7.3	2.79
STR	7.1	2.28
SUA	7.1	1.60
SEP	6.9	2.96
CPA	6.8	3.01
ANG	6.8	2.39
VDF	6.7	2.87
VAS	6.3	2.83
PRF	5.9	2.42
FAC	5.4	3.57
WND	4.1	3.14

t-Test: Two-Sample Assuming Equal Variances
DNS vs. DNS x WND

	Variable 1	*Variable 2*
Mean	7.2	4.1
Variance	5.73333333	9.87777778
Observations	10	10
Pooled Variance	7.80555556	
Hypothesized Mean Difference	0	
df	18	
t Stat	2.48110296	
P(T<=t) one-tail	0.01160034	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.02320068	
t Critical two-tail	2.10092367	

Here again, we see a justification for why the statistical data may not be a meaningful way to assign weightings. There is no reason to believe that the presence of wind [WND], combined with aircraft density [DNS] would *reduce* the absolute level of complexity compared to the absolute level of complexity associated with density alone. If there were no additional amount of complexity added by the presence of wind, then one would expect to see the combined factor rating [DNS x WND] to be the same as the single factor rating ([DNS] = 7.2).

Number of Aircraft Climbing or Descending [CoD]

Absolute Rating: 6.4

A simple numerical count of the number of aircraft expected to climb or descend in altitude.

Again, in general, controllers agreed that an increase in the number of aircraft climbing or descending within a sector results in an increase in the complexity associated with the control of that sector. However, the relationship between the number of aircraft climbing or descending and complexity depends on the density of aircraft [DNS], the number of conflicting altitude pairs [CAP], the intentions of the aircraft [INT], and type of sector being worked [STR]. In general, most controllers stated that if you are controlling an arrival or departure sector, then the impact of an increase in the number of aircraft climbing or descending isn't as great as if you were working an overflight sector. Most of the answers given in the interviews were given with the assumption that the controller was working an overflight sector, and some existing condition is forcing aircraft to climb or descend.

When asked to give a range of the number of aircraft climbing or descending that they consider to be very high, high, and low in complexity, most answers were given in terms of the percentage of the total number of aircraft. The numbers below, of course, depend on the total number of aircraft within the sector (as in DNS). Therefore, controllers assumed "moderate" levels of traffic when stating their answers.

	μ	$\sigma^{(n-1)}$
Very High	>52%	14.6
High	>31%	8.6
Low	<23%	6.5

In addition, one controller mentioned that as the percentage gets closer to 100, it becomes slightly easier because then everyone is doing the same general thing. With respect to time, controllers feel that looking ahead about 15 minutes is reasonable to determine the number of aircraft that will be climbing or descending.

DNS	8	2.36
CAP	7.1	2.13
INT	7.1	1.60
STR	7	2.11
NBR	6.6	3.06
PRX	6.3	2.71
PRF	6.2	2.62
VAS	6	3.50
ANG	6	2.45
CRD	6	3.16
FAC	5.8	3.22
CPA	5.8	2.62
VDF	5.7	3.59
SEP	5.6	2.07
SUA	4.9	3.07
WND	4.3	2.21

t-Test: Two-Sample Assuming Equal Variances
CoD vs. CoD x WND

	Variable 1	*Variable 2*
Mean	6.4	4.3
Variance	4.26666667	4.9
Observations	10	10
Pooled Variance	4.58333333	
Hypothesized Mean Difference	0	
df	18	
t Stat	2.19337847	
P(T<=t) one-tail	0.02082716	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.04165432	
t Critical two-tail	2.10092367	

Distribution of Closest Points of Approach [CPA]

Absolute Rating: 6.5

This measure is a time-based distribution of the number of intersecting (laterally) flight paths which could be potential conflicts.

We asked controllers to give a distance (in terms of miles) of how closely two aircraft are expected to cross that will cause them to carefully watch the situation, in case action will need to be taken. As well, we asked controllers to give a predicted crossing distance that they will automatically act upon, to ensure separation. We asked the controllers to assume a moderate traffic load when giving their answers. This data is presented below, with measurements in miles:

	μ	$\sigma^{(n-1)}$
Concern	<13	2.27
Action	<8.2	1.09

Finally, we asked controllers to determine the amount of time necessary to examine the effects a potential conflict could have on the complexity of their job. As with most conflicts, controllers stated that about 8 minutes is what they have right now (based on their trend vectors), but some mentioned that 10 -15 minutes might be more helpful, in certain situations.

Controllers rated the fact that the distribution of closest points of approach, combined with the issue of intent [INT] is fairly high in complexity. As well, the number of crossing altitude profiles [CAP], combined with the distribution of closest points of approach results in relatively high complexity.

INT	7.5	3.03
CAP	7	2.91
DNS	6.8	3.01
PRX	6.7	1.95
NBR	6.1	2.56
CoD	5.8	2.62
VDF	5.8	2.30
STR	5.6	2.32
CRD	5.6	2.76
SUA	5.4	2.55
VAS	5.4	2.17
FAC	5.3	3.13
SEP	5	2.36
PRF	4.9	2.33
ANG	4.6	3.37
WND	4.4	2.67

Number of Crossing Altitude Profiles [CAP]

Absolute Rating: 7.2

This measure is an examination of the number of ascending and descending aircraft profile pairs that are expected to occupy (in crossing) the same altitude within a specified period of time in the future.

Controllers agree that an increase in the number of aircraft pairs expected to occupy the same altitude (in crossing) results in a higher level of complexity. During the interviews, the controllers stated that is somewhat dependent upon the sector and the way it is designed. However, in the factor pairs ratings, we found that CAP x STR was not rated to be high in complexity.

Looking at a percentage matrix (as above), the following information was collected. Again, this percentage is based on the density of the aircraft.

	μ	$\sigma^{(n-1)}$
Very High	>37%	13.3
High	>25%	5.5
Low	<19%	6.6

Some controllers stated that 15 - 20 minutes is a reasonable amount of time to look ahead to examine the impact that this factor will have on complexity. The reason these numbers, in terms of percentages, are generally lower than those of the previous question is because of the simultaneous mental calculations required for each pair. As the number of aircraft pair increase, the calculations get more difficult at a faster rate.

INT	7.8	1.48
DNS	7.6	1.96
PRX	7.3	2.21
CoD	7.1	2.13
PRF	7	1.94
CPA	7	2.91
NBR	6.7	2.87
SEP	6.7	1.77
ANG	6.6	2.59
VAS	6.4	2.91
CRD	6.1	3.07
VDF	5.7	3.43
STR	5.6	2.37
FAC	5.3	3.16
WND	5.2	2.90
SUA	4.8	2.66

t-Test: Two-Sample Assuming Equal Variances
CAP vs. CAP x SUA

	Variable 1	*Variable 2*
Mean	7.2	4.8
Variance	4.17777778	7.06666667
Observations	10	10
Pooled Variance	5.62222222	
Hypothesized Mean Difference	0	
df	18	
t Stat	2.26330061	
P(T<=t) one-tail	0.01810682	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.03621364	
t Critical two-tail	2.10092367	

The possible reasons for, and the implications of, this finding have been described above in the introduction to this document.

Prox. of Potential Conflicts to Sector Boundary [PRX]

Absolute : 6.0

This measure is an examination of the location(s) of the potential conflict(s) with respect to current sector boundaries.

In general, controllers feel that when a conflict is expected to be closer to sector boundaries, the complexity of that conflict situation increases. This increased complexity is primarily due to the fact that the coordination required with other sectors is increased and that the controller typically has less time available to resolve the situation. In addition, an increase in the number of aircraft predicted to conflict at a single point increases the complexity.

One controller stated that any predicted conflicts that are inside of 10 miles to a sector boundary will typically result in a more complex situation to handle. Other controllers felt that there was still some degree of complexity associated with conflicts that fall within a 15 mile range of a sector boundary. Finally, a few controllers were a bit more conservative and stated that anything inside a 25 - 30 mile range to a boundary greatly increases the complexity of the conflict.

With respect to the amount of time desired to prepare for these close-to-the-boundary conflicts, some controllers would like to know about 12-15 minutes ahead of time. While it might be more useful for them to have the information earlier, most controllers stated that anything beyond 15 minutes was probably not very meaningful. Finally, three controllers stated that this issue (time to predict conflict) is related to the angle of the predicted conflict. Shallower angles of conflict would require more time for notification. However, this does not show up in the data presented below.

INT	8.2	1.93
DNS	8	1.41
CAP	7.3	2.21
NBR	7.2	2.97
CRD	7.2	1.81
CPA	6.7	1.95
CoD	6.3	2.71
STR	6.2	1.48
FAC	6	2.83
ANG	5.8	2.86
SEP	5.7	2.21
VAS	5.2	2.86
SUA	5	2.26
VDF	4.4	2.50
PRF	4.4	2.07
WND	3.8	1.87

t-Test: Two-Sample Assuming Equal Variances
PRX vs. PRX x DNS

	Variable 1	*Variable 2*
Mean	6	8
Variance	3.77777778	2
Observations	10	10
Pooled Variance	2.88888889	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.6311741	
P(T<=t) one-tail	0.00847468	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.01694936	
t Critical two-tail	2.10092367	

t-Test: Two-Sample Assuming Equal Variances
PRX vs. PRX x INT

	Variable 1	*Variable 2*
Mean	6	8.2
Variance	3.77777778	3.73333333
Observations	10	10
Pooled Variance	3.75555556	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.5384615	
P(T<=t) one-tail	0.01029512	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.02059023	
t Critical two-tail	2.10092367	

t-Test: Two-Sample Assuming Equal Variances
PRX vs. PRX x WND

	Variable 1	*Variable 2*
Mean	6	3.8
Variance	3.77777778	3.51111111
Observations	10	10
Pooled Variance	3.64444444	
Hypothesized Mean Difference	0	
df	18	
t Stat	2.57686707	
P(T<=t) one-tail	0.0095001	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.01900021	
t Critical two-tail	2.10092367	

Examining the interview data, as well as the absolute factor pair ratings, we can see that the issue of proximity to sector boundaries [PRX], combined with the knowledge of intent [INT] results in fairly high complexity. This makes sense due to the fact that when a conflict is close to a sector boundary, the controller needs to know exactly where that aircraft intends to fly due to the coordination [CRD} required. Also, the complexity associated with [PRX] and density [DNS] is also rated high probably due, again, to the fact that conflicts near boundaries are more complex and require more effort (in terms of coordination).

Angle of Convergence in Conflict Situation [ANG]

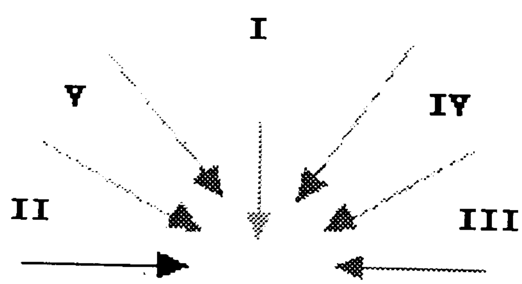
Absolute Rating: 6.0

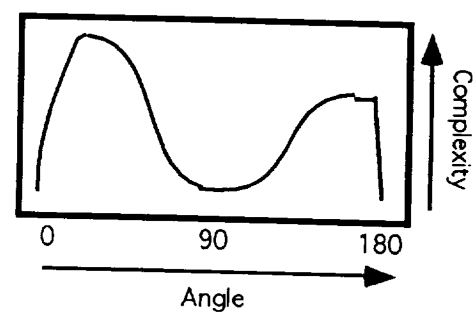
A measure that examines the predicted angle of convergence in a conflict.

In general, controllers stated that shallower angles of convergence result in a longer period of potential conflict and require action to be taken sooner. Thus, the complexity is increased. However, there are some interesting specifics about various angles worth mentioning:

All controllers agree that as angles get below 25° or 30°, the complexity becomes much greater than if they were presented with a close-to-90° situation.

One controller drew out the following graphic (presented on the left) to describe the relative levels of complexity between different angles of convergence. As the numerical value of each section increases (From I to V), the complexity associated with that angle of convergence increases. Angle lines are approximately 30° in separation. Another controller drew a different graphic to describe the relative levels of complexity associated with varying angle of convergence in a conflict situation. This has been modified based on information obtained from other controllers, and is presented below on the right:





With respect to the time of prediction for these conflict situations, most controllers feel that the time, in minutes, should correspond with the relative level of complexity, because as the complexity of a conflict increases, the time needed to resolve that conflict increases as well. The range of these times should be from 8 to about 15 minutes.

INT		7.1	3.03
DNS		6.8	2.39
NBR		6.8	3.08
CAP	6.6		2.59
VDF		6.2	2.20
CoD		6	2.45
WND		5.9	3.45
PRX		5.8	2.86
VAS		5.1	2.47
SEP		5.1	2.81
PRF		4.7	2.26
CPA		4.6	3.37
STR		4.4	2.37
FAC		4.3	2.67
CRD		4.3	2.91
SUA		3.9	2.73

Again, we see the impact that intent information [INT] has on the complexity of the situation. This time, when the issue of intent is combined with the angle of convergence, the complexity is rated fairly high due to the fact that the degree of turn required to solve a conflict situation is partly determined on the knowledge of where the aircraft are going to be in the near future.

Coordination [CRD]

Absolute Rating: 6.7

An examination of the impact that the presence of aircraft that require some form of coordination (with other sectors, etc.) for proper control has on the complexity of an air traffic situation.

Throughout the entire interview process, controllers consistently stated that situations which require coordination have the potential to increase the complexity of control. Coordination between sectors can be problematic at times, but in general it is considered manageable.

If one examines the absolute ratings of the combined factors, it can be seen that issues such as density [DNS], the proximity of a conflict to a sector boundary [PRX], and the number of facilities [FAC], when combined with the requirement for coordination, result in higher complexity.

DNS	**7.3**	**2.79**
PRX	**7.2**	**1.81**
FAC	**7**	**3.13**
SEP	6.4	2.99
INT	6.2	3.33
CAP	6.1	3.07
STR	6	2.79
CoD	6	3.16
SUA	5.6	3.10
CPA	5.6	2.76
NBR	5.4	2.80
VDF	5.2	2.94
PRF	4.5	3.10
WND	4.4	3.63
ANG	4.3	2.91
VAS	4.2	3.19

Neighbors [NBR]

Absolute Rating: 6.7

This factor concerns the distance between aircraft pairs in conflict and other aircraft within some parameter distance or time.

Many controllers stated that if neighboring aircraft are within 8-10 miles of a conflict, then the complexity associated with the presence of that neighbor is very high. However, other controllers were more conservative; some stated that the presence of other aircraft within 15-20 miles of a conflict situation is enough to impact the complexity.

INT	**8**	**3.09**
DNS	**7.4**	**2.80**
PRX	**7.2**	**2.97**
ANG	6.8	3.08
CAP	6.7	2.87
CoD	6.6	3.06
CPA	6.1	2.56
SEP	5.7	2.98
SUA	5.5	2.80
WND	5.5	2.76
CRD	5.4	2.80
VDF	5.3	2.67
STR	5.2	3.05
PRF	4.9	2.73
VAS	4.8	3.01
FAC	4.3	3.09

Separation Requirements [SEP]

Absolute Rating: 6.3

A measure that examines the impact that imposed separation requirements for longitudinal sequencing and spacing have on complexity.

In the interviews, controllers agreed that the complexity of air traffic control is increased when separation restrictions are required (i.e., miles in trail to Chicago, for example). This complexity increases when the controllers are not given enough time to prepare for these separations. Therefore, some controllers would like to have at least 20 - 30 minutes notice that additional (above 5 miles) separation requirements are needed. Two controllers stated that even though 20 - 25 minutes notice is typically given, they would like about 40 minutes notice, in order to facilitate planning and to help with the distribution of the complexity over other sectors. The knowledge of intent [INT] is the only factor that, combined with additional separation requirements results in a complexity of above 7.0.

INT	7.2	3.05
DNS	6.9	2.96
CAP	6.7	1.77
CRD	6.4	2.99
PRX	5.7	2.21
NBR	5.7	2.98
CoD	5.6	2.07
VAS	5.2	2.25
ANG	5.1	2.81
CPA	5	2.36
SUA	4.9	2.64
FAC	4.9	2.42
PRF	4.9	2.51
VDF	4.8	2.70
STR	4.4	2.84
WND	4.3	2.71

Variance in Directions of Flight [VDF]

Absolute Rating: 5.1

A measurement that looks at the variability of direction for each aircraft to be controlled.

The controllers agreed that if all of the aircraft within a sector are moving in the "same" direction, then the complexity associated with the direction of flight is not considered to be an impact.

One of the possible problems with everyone traveling in the same direction is the shallower angles of convergence seen in conflict situations. This requires the controller to have to look further ahead in order to predict/resolve a conflict situation, and the conflicts themselves are more difficult to solve. Also, the issue of intent [INT] is very important in this situation as well. If a controller does not have knowledge of the intent of an aircraft, then s/he will probably have to more closely monitor the situation to be sure that no conflicts will occur.

INT	**8**	**1.83**
DNS	6.7	2.87
ANG	6.2	2.20
CPA	5.8	2.30
CoD	5.7	3.59
CAP	5.7	3.43
STR	5.3	2.58
WND	5.3	2.83
NBR	5.3	2.67
CRD	5.2	2.94
SEP	4.8	2.70
VAS	4.6	2.41
FAC	4.5	2.99
PRX	4.4	2.50
SUA	4.3	2.26
PRF	4.3	1.83

t-Test: Two-Sample Assuming Equal Variances
VDF vs. VDF x INT

	Variable 1	*Variable 2*
Mean	5.1	8
Variance	4.54444444	3.33333333
Observations	10	10
Pooled Variance	3.93888889	
Hypothesized Mean Difference	0	
df	18	
t Stat	-3.2673536	
P(T<=t) one-tail	0.0021393	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.00427861	
t Critical two-tail	2.10092367	

Airspace Structure [STR]

Absolute Rating: 5.2

This measurement will examine the impact that sector size and structure has on the complexity of air traffic control.

Overall, controllers feel that there is not a big difference between sector shapes with respect to complexity. One controller stated that larger, more round sectors *might* be more difficult because of the increased amount of airspace that you need to deal with. However, for long, narrow sectors, which are smaller in size, such as those typically associated with arrivals into an airport, you are required to look farther outside the sector (in terms of time) to predict potential traffic conflicts, and you have to increase your scan rate because you have less time to deal with situations. Both of these factors can potentially increase the complexity of a given situation. According to the interview results, smaller sectors also require an increase in the amount of communication / coordination needed for effective traffic control. On the other hand, larger sectors typically allow one controller more time to formulate a plan and see it through.

For most of the controllers, the difficulty associated with any sector mainly comes from aircraft that are present in the sector that are behaving differently from the intended design of the sector. For example, in a long, narrow, arrival sector, complexity increases when traffic crosses "against the grain" of the sector (either directional, as in north or southbound overflight traffic flowing through an east-west oriented arrival sector, or on an altitude basis, such as seen with [CoD]). In larger sectors, the larger volume of airspace can actually help in dealing with these type of crossing traffic flows.

The complexity associated with the airspace structure is probably best evaluated by looking at both the shape of the sector and the type of traffic associated with that sector. A number of controllers suggested that the design of the sector itself may in fact be a major contributor to complexity. If a sector is set up wrong (for example, sectors 16, 33, 34) then the complexity increases because of the difficulties associated with trying to "correct" for the bad design of the sector. Another example would be if a really large sector was designed for arrival/departure traffic [CoD].

DNS	7.1	2.28
CoD	7	2.11
PRX	6.2	1.48
CRD	6	2.79
INT	5.9	3.35
CAP	5.6	2.37
CPA	5.6	2.32
FAC	5.3	2.75
VDF	5.3	2.58
NBR	5.2	3.05
SUA	5.1	3.03
VAS	4.7	1.64
ANG	4.4	2.37
SEP	4.4	2.84
PRF	3.4	1.78
WND	3.4	2.91

Performance Mix of Traffic [PRF]

Absolute Rating: 5.1

A measurement that looks at the variance in performance capabilities of current and expected aircraft.

Again, the controllers agreed that if the general performance characteristics of the aircraft are similar, the complexity associated with aircraft performance is relatively low.

As a reference point, one controller gave the following "classes" of jet performance characteristics:

• B737	MD80	A300		
• B727	A310	B757	B767	(new) MD80
• B747	DC10	B777	L1011	

When asked to determine a reasonable amount of time to examine the performance mix of traffic that is expected, some controllers felt that anywhere between 15 and 20 minutes would be helpful. This information is based primarily on the fact that controllers receive flight strips approximately 20 minutes before an aircraft enters their sector. Two other controllers suggested that looking only 8-10 minutes ahead was enough time. This number was based on their 8 minute trend vector line currently available on the FDADs.

INT	7.3	1.89
CAP	7	1.94
CoD	6.2	2.62
DNS	5.9	2.42
VAS	5	2.36
CPA	4.9	2.33
NBR	4.9	2.73
SEP	4.9	2.51
WND	4.7	3.30
ANG	4.7	2.26
CRD	4.5	3.10
PRX	4.4	2.07
VDF	4.3	1.83
FAC	4.2	2.70
STR	3.4	1.78
SUA	3	2.00

t-Test: Two-Sample Assuming Equal Variances
PRF vs. PRF x INT

	Variable 1	*Variable 2*
Mean	5.1	7.3
Variance	6.32222222	3.56666667
Observations	10	10
Pooled Variance	4.94444444	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.212325	
P(T<=t) one-tail	0.02005512	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.04011024	
t Critical two-tail	2.10092367	

Special Use Airspace [SUA]

Absolute Rating: 3.9

This measure is intended to identify how the number/size/activity of restricted areas, warning areas, and military airspace impact the complexity of an air traffic scenario.

Some controllers feel that an SUA located near sector boundaries increases the complexity due to the increase in point-outs and communications that must take place, especially if they are close to the boundaries of multiple sectors. However, two controllers stated that an SUA located in the "middle" of a sector requires that controller to do more work with respect to merging traffic, and, for the most part, that controller alone is primarily responsible for solving any problems.

Somewhat contrary to that point, the location of the SUA with respect to the sector boundaries may not have a significant impact on complexity. Most controllers stated that the amount of complexity is based on the location and/or size of the SUA with respect to established traffic patterns. For example, if an SUA is located so that it blocks a specific traffic flow pattern (for example, climbing and descending traffic), the complexity that results from this SUA can greatly increase.

With respect to the size of an SUA, most controllers stated that a bigger SUA results in greater complexity, most notably because its presence reduces the amount of available airspace [DNS] you have for controlling a/c and increases the amount of work you have with respect to merging traffic. Also, bigger SUAs mean that you have the potential for increased coordination, which takes time away from controlling aircraft, which in turn increases the complexity. However, in the combined ratings, the issue of coordination did not seem to be as great a factor.

In the current ATC system, controllers are given anywhere between 1 and 2 hours of prior notification that an SUA is expected to become active, depending on the TMU/supervisor present. Some controllers give themselves about 10-15 minutes prior to this expected "hot" time to start making plans for action. Other controllers base this preparation time on the relative size of the SUA. For example, for smaller SUAs, they will start planning anywhere from 15-30 minutes prior to that SUA becoming active. For larger SUAs, they will start planning about 45 minutes ahead of time.

DNS	**7.1**	**1.60**
INT	6.2	3.68
CRD	5.6	3.10
NBR	5.5	2.80
CPA	5.4	2.55
STR	5.1	3.03
PRX	5	2.26
CoD	4.9	3.07
SEP	4.9	2.64
CAP	4.8	2.66
FAC	4.3	3.30
VDF	4.3	2.26
ANG	3.9	2.73
VAS	3.6	2.12
PRF	3	2.00
WND	2.3	2.21

t-Test: Two-Sample Assuming Equal Variances
SUA vs. SUA x DNS

	Variable 1	*Variable 2*
Mean	3.9	7.1
Variance	4.1	2.54444444
Observations	10	10
Pooled Variance	3.32222222	
Hypothesized Mean Difference	0	
df	18	
t Stat	-3.9257319	
P(T<=t) one-tail	0.00049547	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.00099094	
t Critical two-tail	2.10092367	

Number of Facilities [FAC]

Absolute Rating: 5.0

A simple count of the number of facilities being served by, or contained within, the sector.

In general, controllers stated that as the number of facilities (defined by controllers as either airports or other ARTCCs) increased, the complexity increases. This is mainly due to the increased amount of coordination that is required [CRD]. The relationship between the number of facilities and the complexity of control is not linear, however. In fact, many controllers stated that the relationship is probably better approximated exponentially.

Although some controllers stated that 3 or more facilities typically results in significantly greater complexity, there are additional factors that need to be considered. For example, the impact that an extra facility may have depends upon the level of activity associated with those facilities. The more active those facilities are, the more complex the situation becomes.

Finally, controllers stated that the impact that an increased number of facilities (in terms of airports) has is generally more apparent in lower altitude sectors. For example, if that additional facility is an airport, then the complexity greatly depends upon whether or not that airport is served by a TRACON. If it is, then the complexity isn't as bad as when an ARTCC controller also needs to control the approach for that airport.

CRD	7	3.13
PRX	6	2.83
CoD	5.8	3.22
INT	5.6	3.57
DNS	5.4	3.57
STR	5.3	2.75
CAP	5.3	3.16
CPA	5.3	3.13
SEP	4.9	2.42
VAS	4.8	2.57
VDF	4.5	2.99
SUA	4.3	3.30
ANG	4.3	2.67
NBR	4.3	3.09
PRF	4.2	2.70
WND	3.7	3.27

Variance in Aircraft Speed [VAS]

Absolute Rating: 4.3

A measurement that looks at the variability of speed tracked for each aircraft.

In general, the controllers agreed that if there was a high level of variance in aircraft speeds, then the complexity of that situation would increase, especially with respect to overtakes.

When asked about the "equality" of speeds, many controllers stated that aircraft speed differences below 20 kts [for jets] are generally considered to be equal, and therefore the complexity associated with 20 kt differences in aircraft speeds is fairly low. Some controllers continued, saying that speed differences of 30 - 50 kts generates some complexity because they are different enough to warrant concern, and that speed differences above 50 kts greatly increases the complexity.

An interesting point is the fact that the complexity associated with speed differences depends greatly upon their current separation. For example, if two aircraft are 20 miles apart, and the second aircraft has a 20 kt overtake, it will be quite some time before action needs to be taken. If, however, they are only separated by 8 miles, then actions to prevent an overtake conflict need to be taken more quickly.

Because controllers view aircraft speeds in terms of miles-per-minute, many controllers feel that this range remains constant under high and low speeds. However, others feel that the range differs (and is increased) at higher speeds (400+ kts). All controllers agreed that at higher speeds (especially for a head-on conflict situation), action must be taken much earlier, and therefore it makes sense to look further ahead in time to determine the impact that this factor will have on the complexity. A few controllers also mentioned that at lower altitudes, speed adjustments are easier to make (since at higher altitudes, aircraft are flying closer to their "optimal" speeds), and therefore, the complexity might be slightly lower.

INT	6.9	1.97
CAP	6.4	2.91
DNS	6.3	2.83
CoD	6	3.50
CPA	5.4	2.17
PRX	5.2	2.86
SEP	5.2	2.25
ANG	5.1	2.47
PRF	5	2.36
FAC	4.8	2.57
NBR	4.8	3.01
STR	4.7	1.64
VDF	4.6	2.41
WND	4.4	2.72
CRD	4.2	3.19
SUA	3.6	2.12

t-Test: Two-Sample Assuming Equal Variances
VAS vs. VAS x INT

	Variable 1	*Variable 2*
Mean	4.3	6.9
Variance	5.34444444	3.87777778
Observations	10	10
Pooled Variance	4.61111111	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.7074195	
P(T<=t) one-tail	0.00721126	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.01442253	
t Critical two-tail	2.10092367	

Winds [WND]

Absolute Rating: 3.2

A measure of the wind speed and azimuth by altitude, and its impact on aircraft performance characteristics.

Throughout the interviews, it was obvious that there was no real answer to the question of whether or not winds impact the complexity of air traffic control. This is partly due to the fact that winds, in general, are a constant factor in ATC, and therefore are considered part of the system. As well, some controllers stated that the impact of strong winds depends upon the direction of the winds with respect to the traffic, the current conflict situation that needs to be addressed, and the altitude (lower altitudes may be more seriously impacted by higher wind speeds).

However, the controllers were asked to describe the wind speeds that they feel somewhat impact the complexity of control, and the wind speeds that they feel have a substantial impact on complexity. This data is presented below, in kts:

	μ	$\sigma^{(n-1)}$
Somewhat	>48.3	14.38
Significant	>84.3	16.18

In addition to wind speeds, controllers were asked to discuss the complexities associated with the direction of the wind with respect to the traffic situation. Although many controllers stated that the differences between tailwinds, headwinds, and crosswinds are situation specific, they did attempt to provide a definitive answer to the posed question. Most controllers feel that tailwinds have the greater impact on complexity due to the impact they can have on aircraft speeds. One controller stated that crosswinds are usually bad for vector operations. Finally, headwinds can actually help in situations that require a turn-out, while in other cases, the headwinds cause aircraft to turn more than expected, which can create problems.

INT	6	3.83
ANG	5.9	3.45
NBR	5.5	2.76
VDF	5.3	2.83
CAP	5.2	2.90
PRF	4.7	3.30
VAS	4.4	2.72
CPA	4.4	2.67
CRD	4.4	3.63
CoD	4.3	2.21
SEP	4.3	2.71
DNS	4.1	3.14
PRX	3.8	1.87
FAC	3.7	3.27
STR	3.4	2.91
SUA	2.3	2.21

t-Test: Two-Sample Assuming Equal Variances
WND vs. WND x ANG

	Variable 1	Variable 2
Mean	3.2	5.9
Variance	3.06666667	11.8777778
Observations	10	10
Pooled Variance	7.47222222	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.2086346	
P(T<=t) one-tail	0.0202034	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.04040681	
t Critical two-tail	2.10092367	

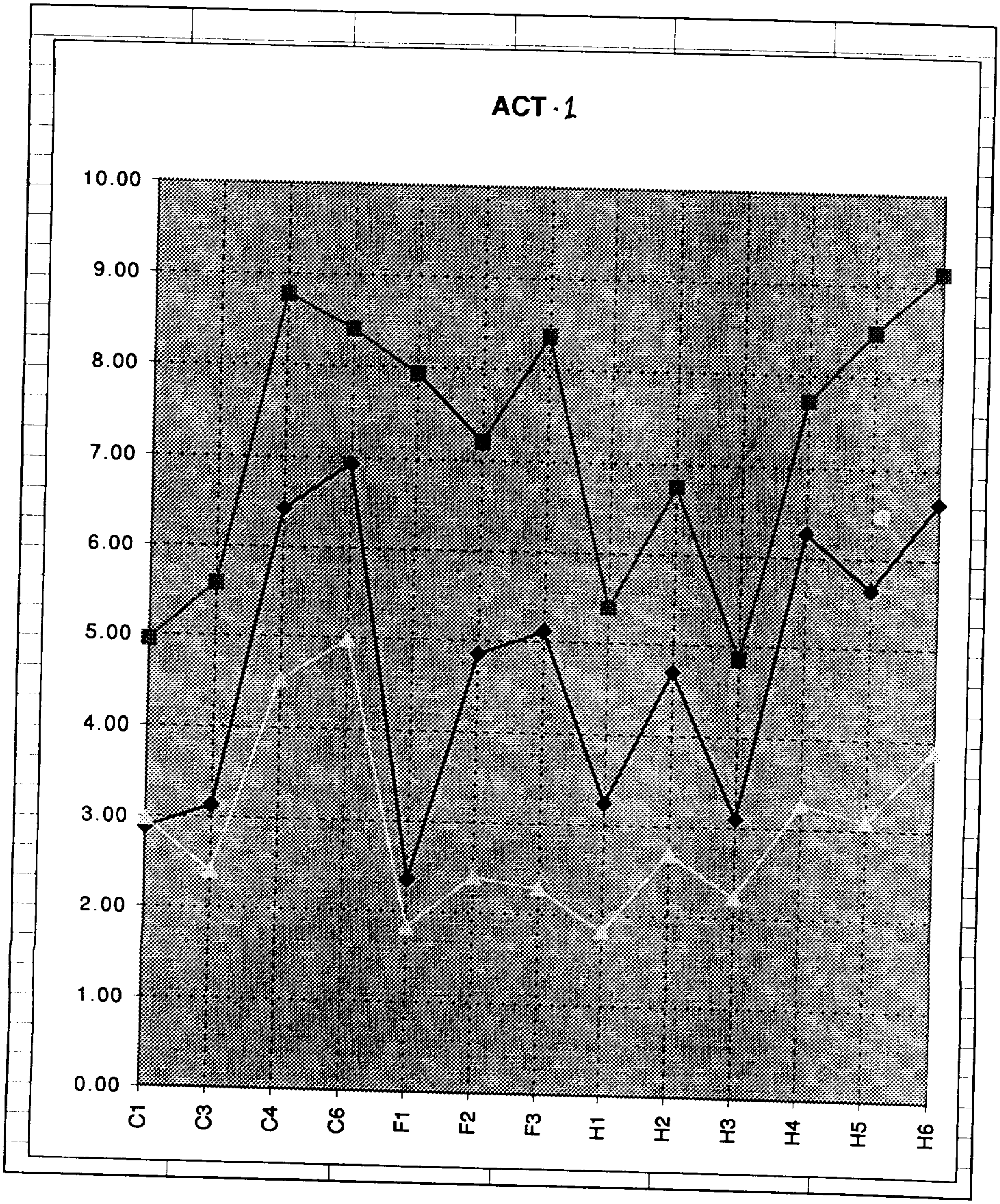
t-Test: Two-Sample Assuming Equal Variances
WND vs. WND x NBR

	Variable 1	Variable 2
Mean	3.2	5.5
Variance	3.06666667	7.61111111
Observations	10	10
Pooled Variance	5.33888889	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.2258065	
P(T<=t) one-tail	0.01952189	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.03904379	
t Critical two-tail	2.10092367	

t-Test: Two-Sample Assuming Equal Variances
WND vs. WND x INT

	Variable 1	Variable 2
Mean	3.2	6
Variance	3.06666667	14.6666667
Observations	10	10
Pooled Variance	8.86666667	
Hypothesized Mean Difference	0	
df	18	
t Stat	-2.1026299	
P(T<=t) one-tail	0.02491647	
t Critical one-tail	1.73406306	
P(T<=t) two-tail	0.04983293	
t Critical two-tail	2.10092367	

APPENDIX C - MEASUREMENT COMPARISON PLOTS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C3
C4
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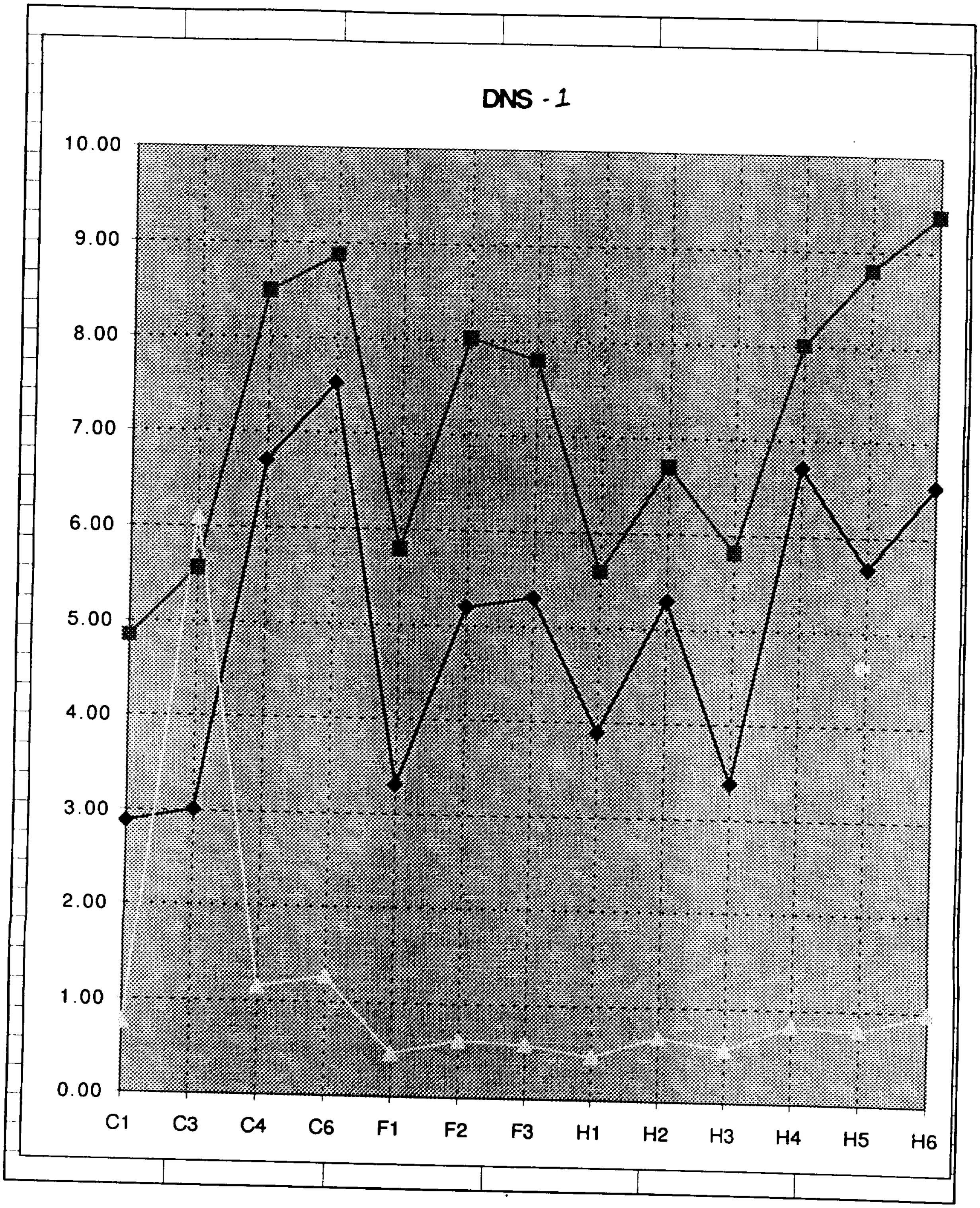
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C6
F1
F2
F3
H1
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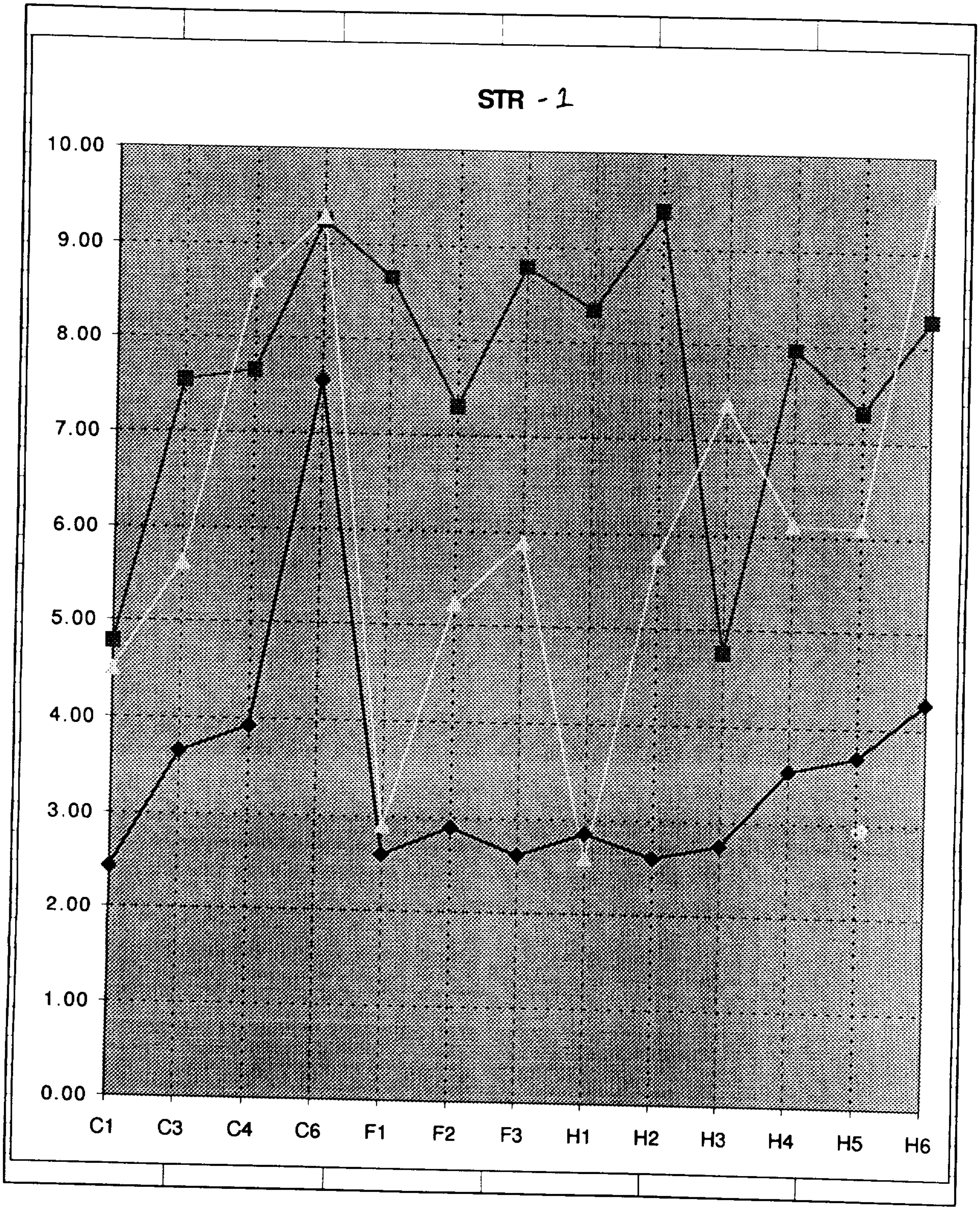
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C4
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F1
F2
F3
H1
H2
H3
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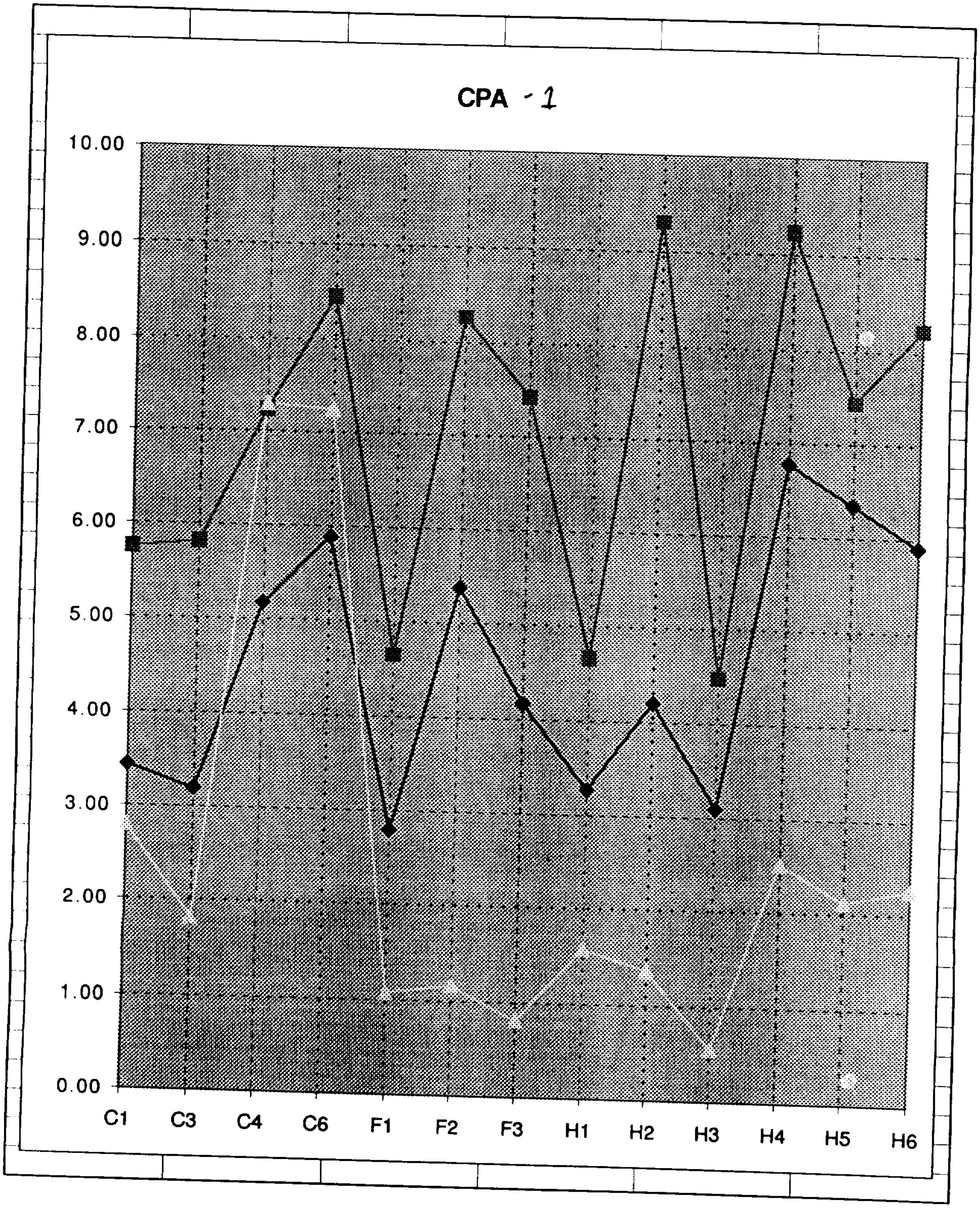
H5
H6



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C4
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H1
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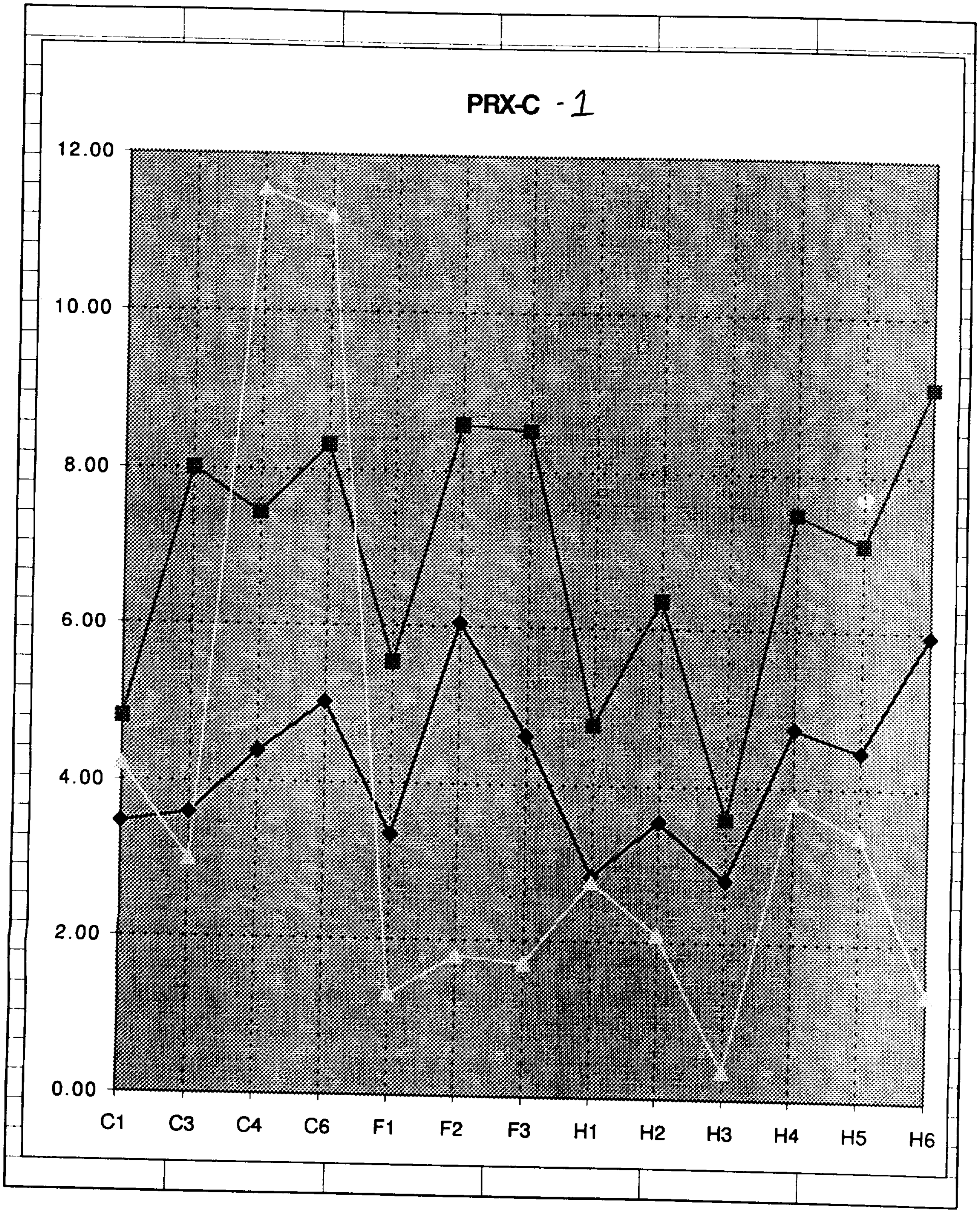
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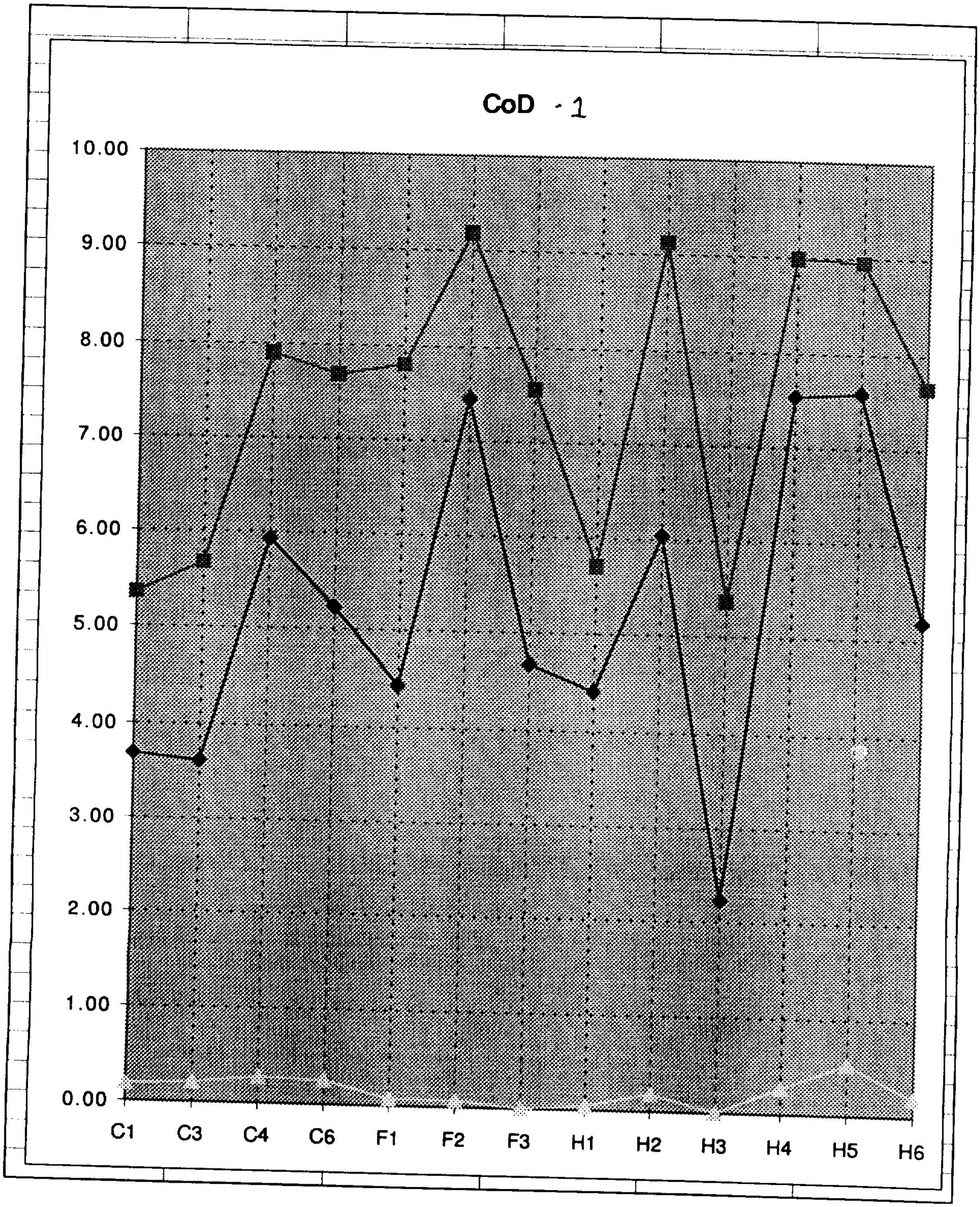

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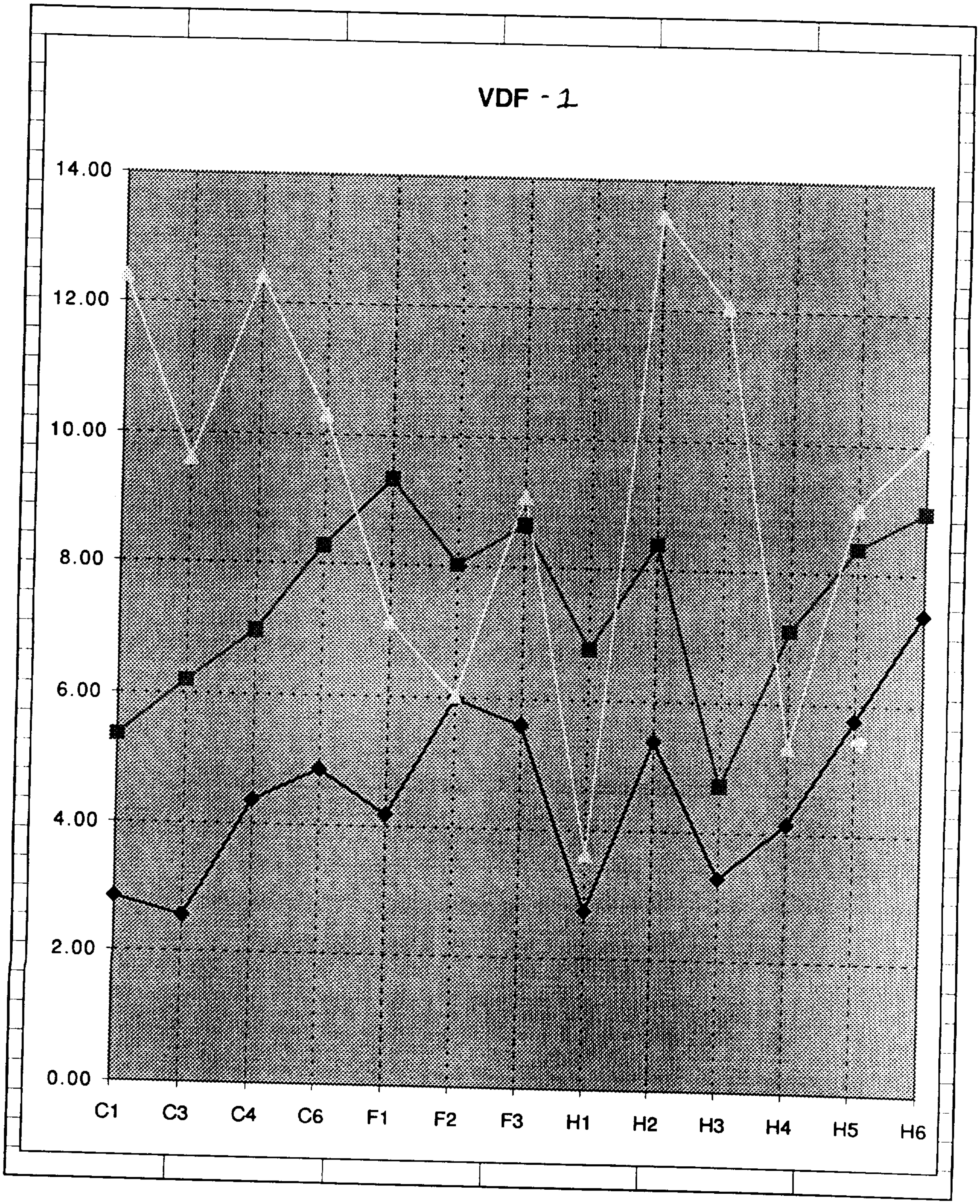

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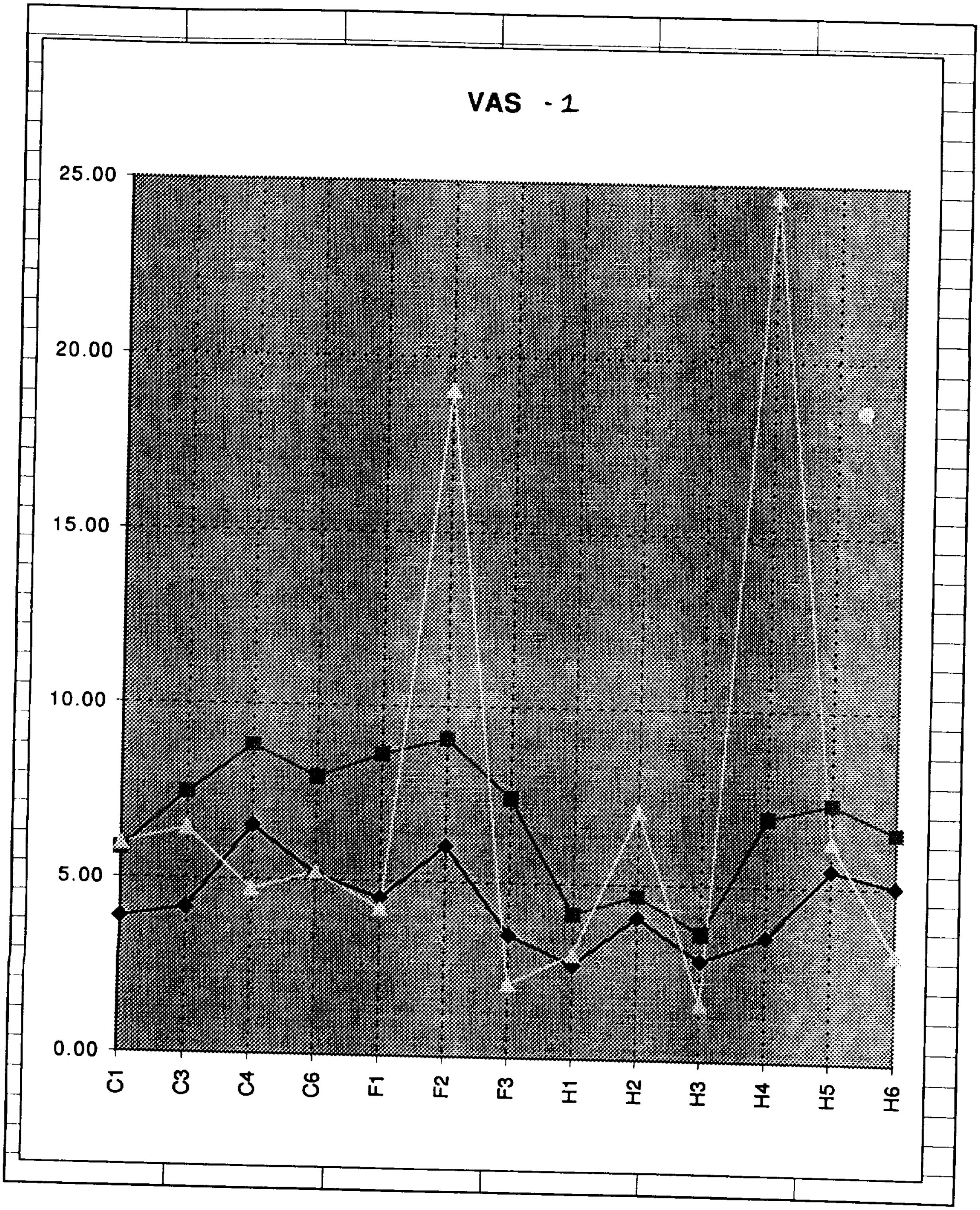
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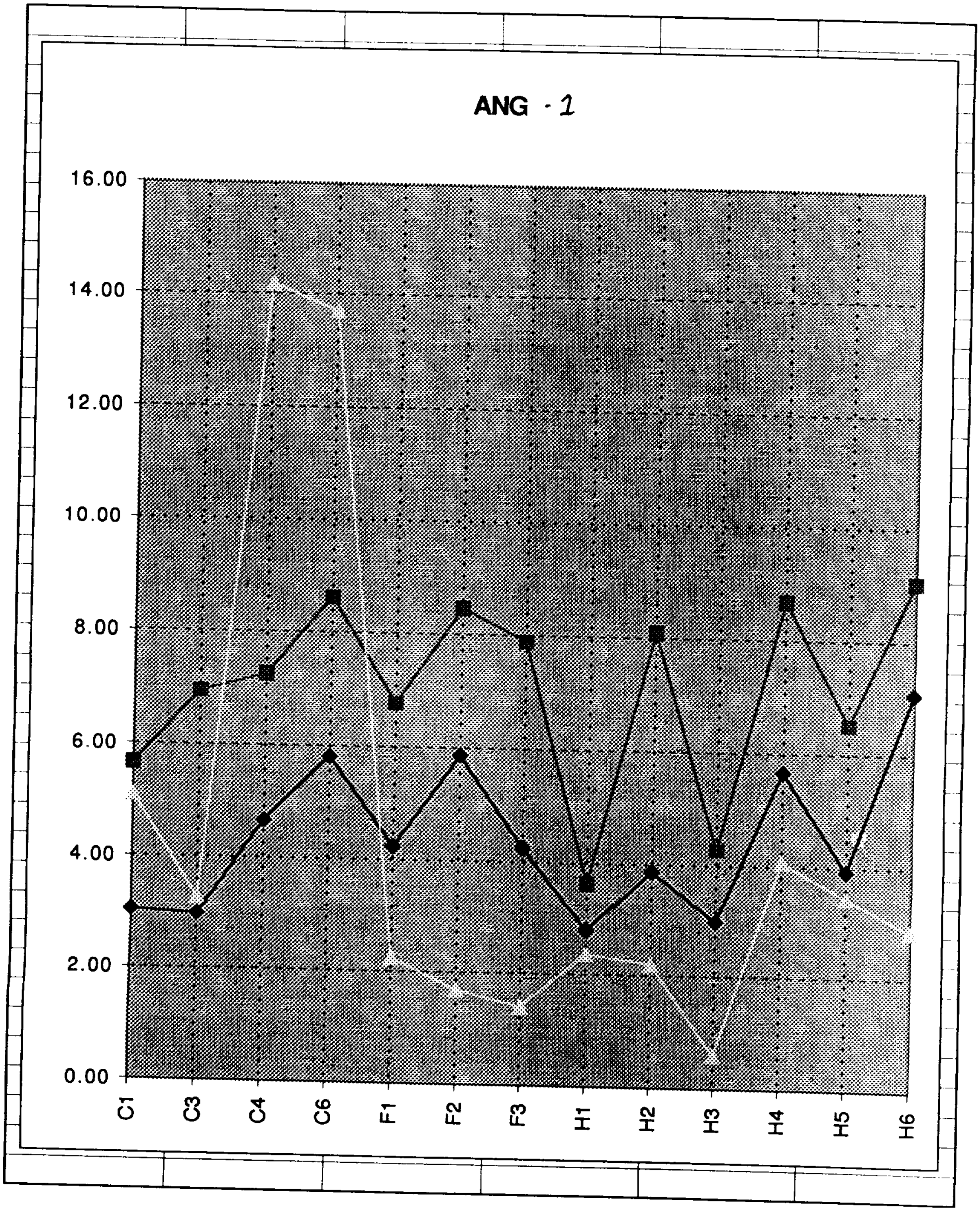
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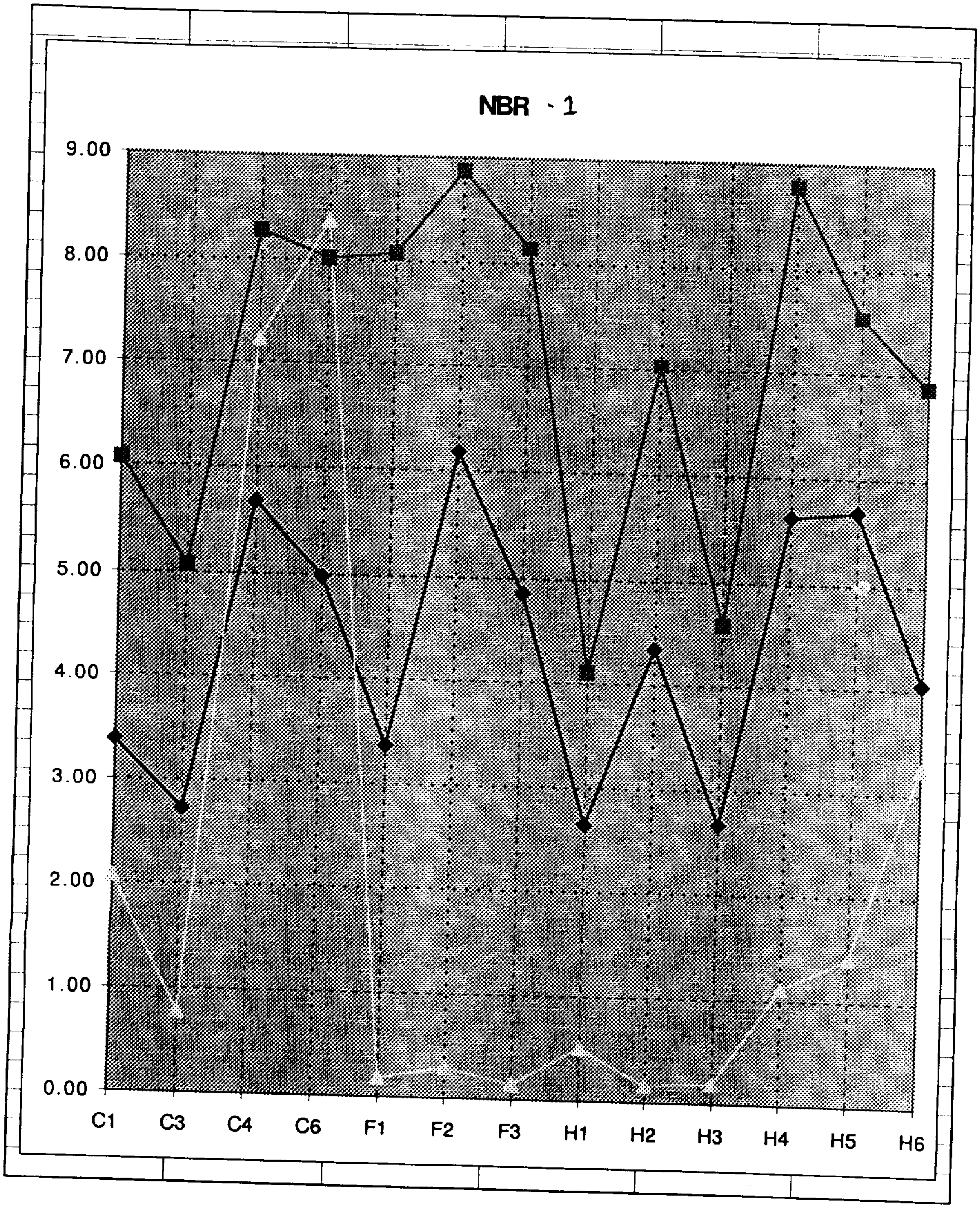
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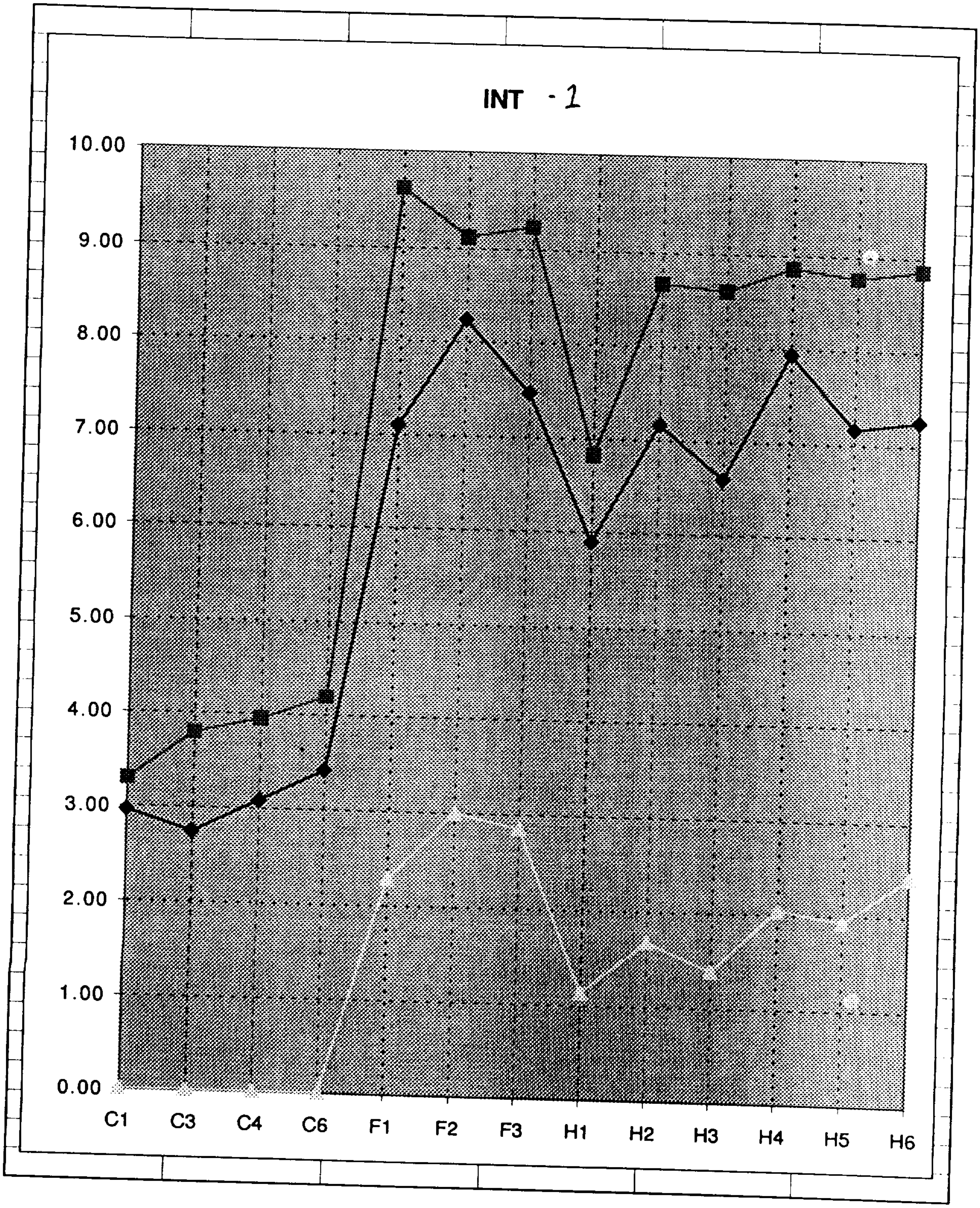
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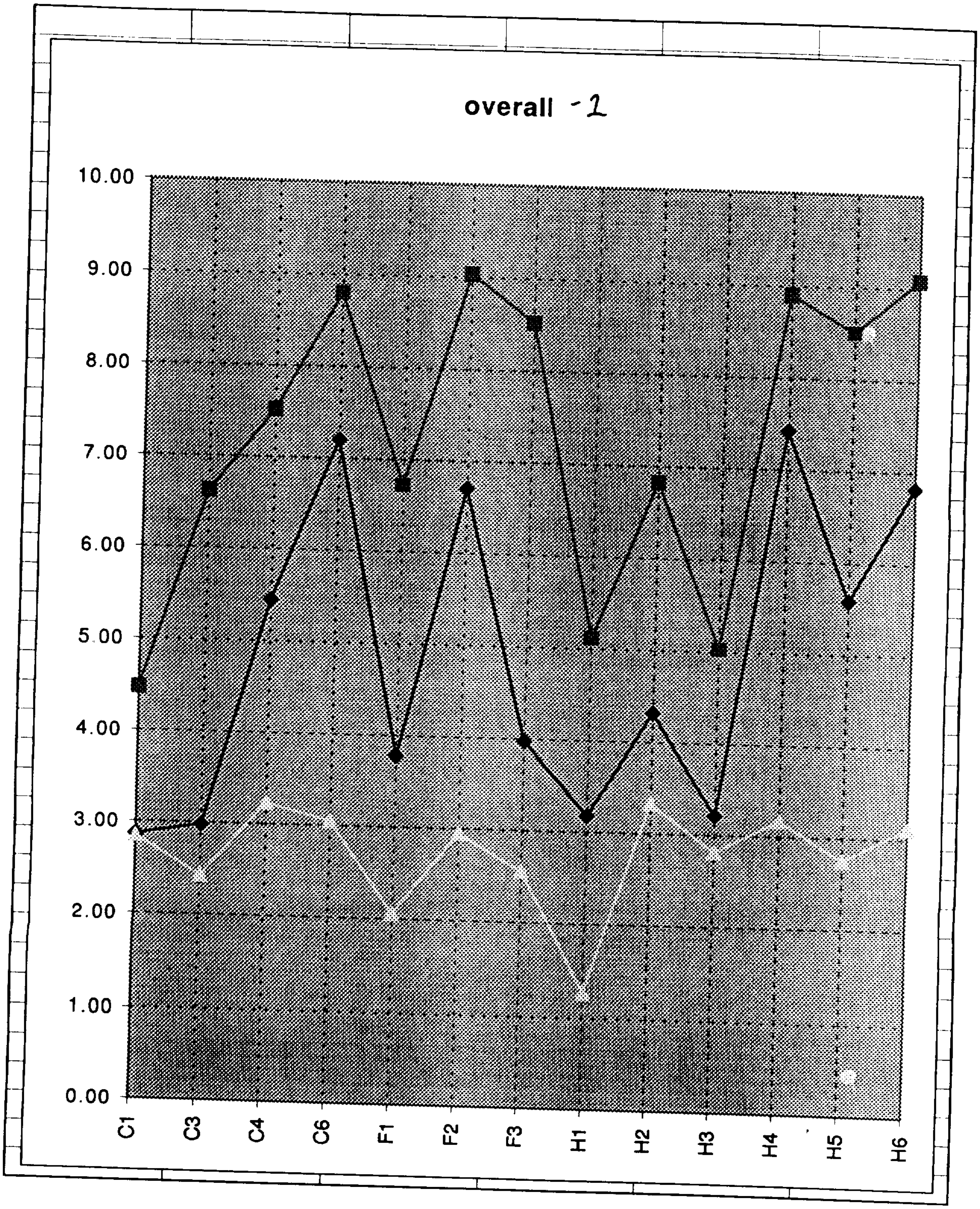
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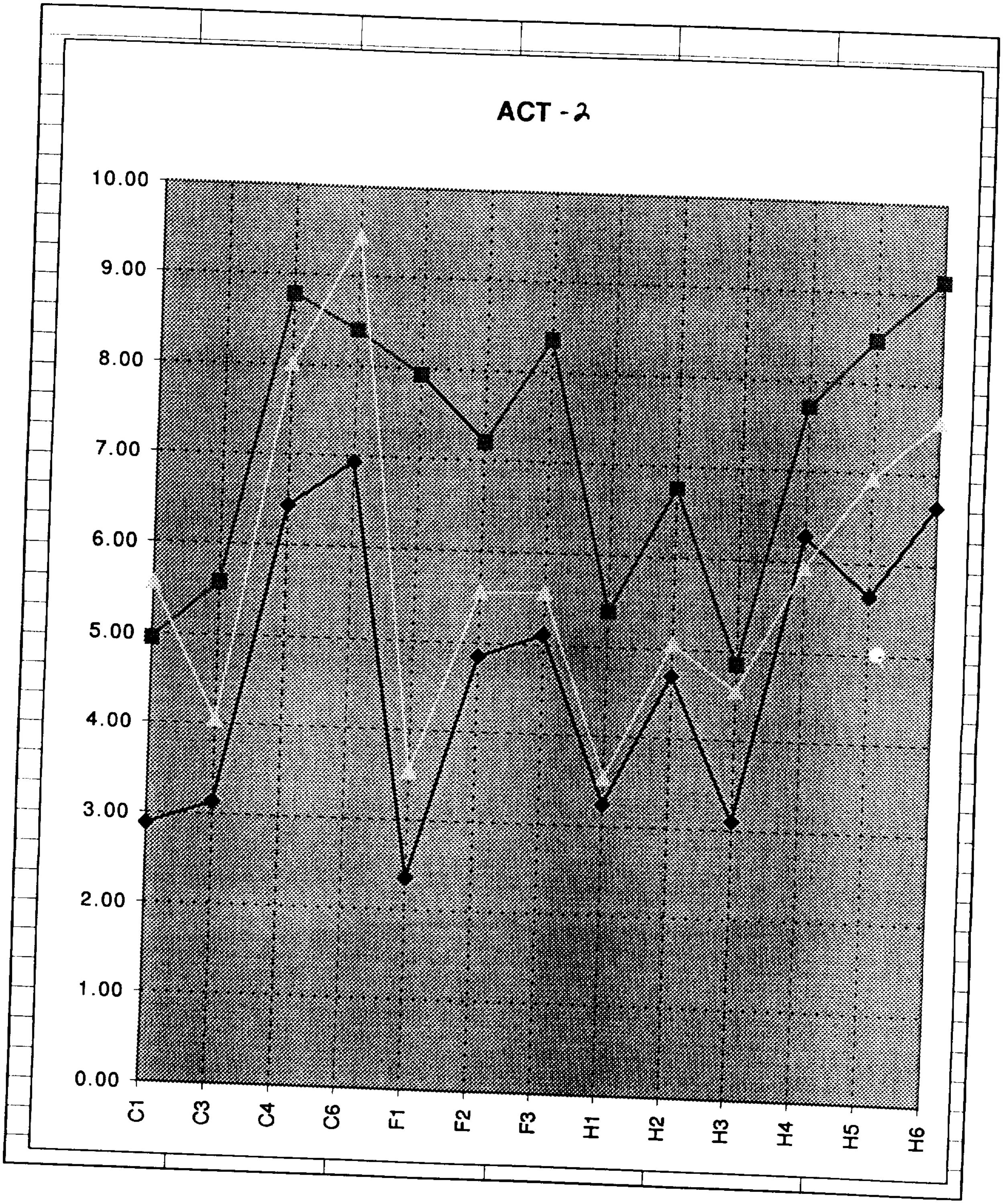
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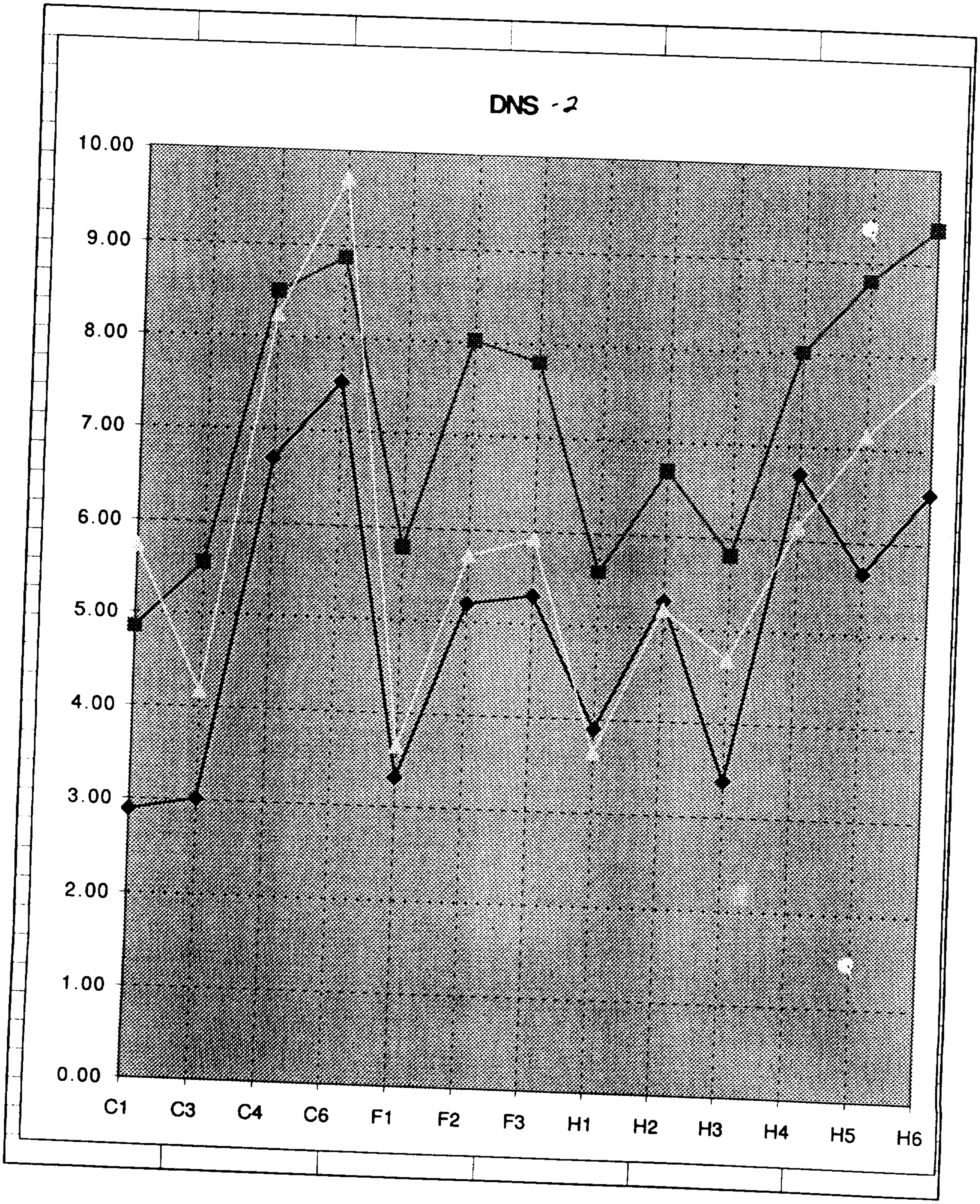
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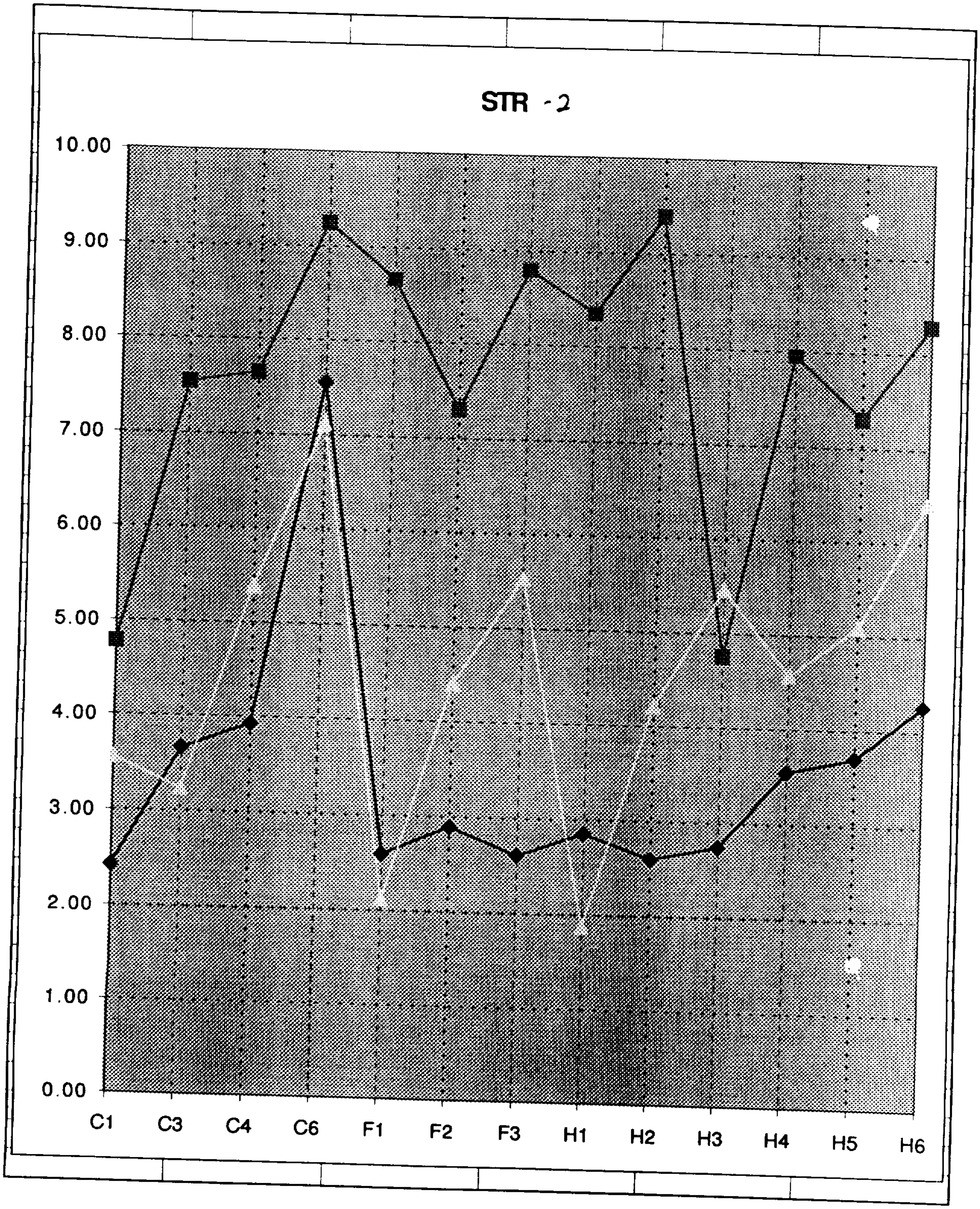
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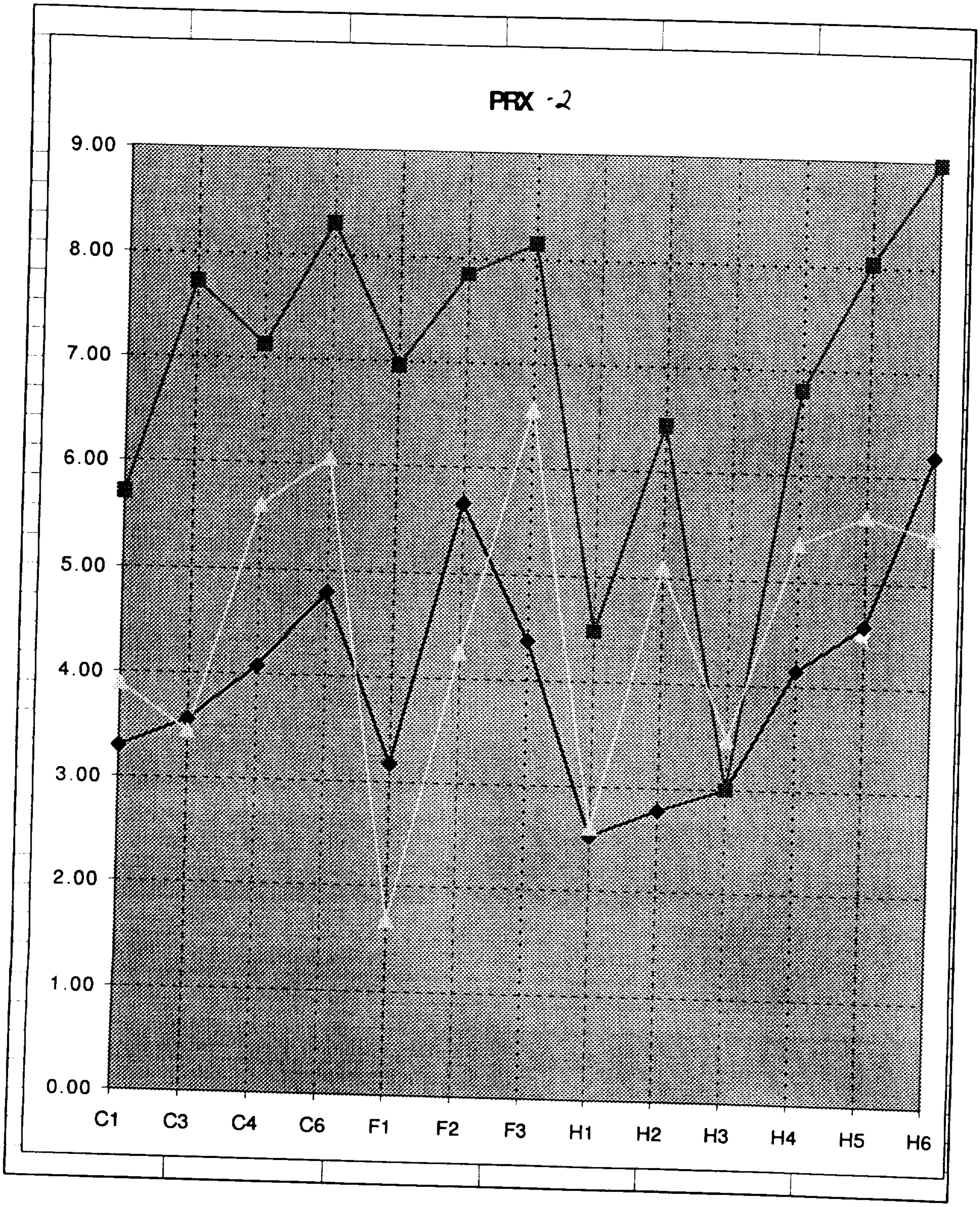
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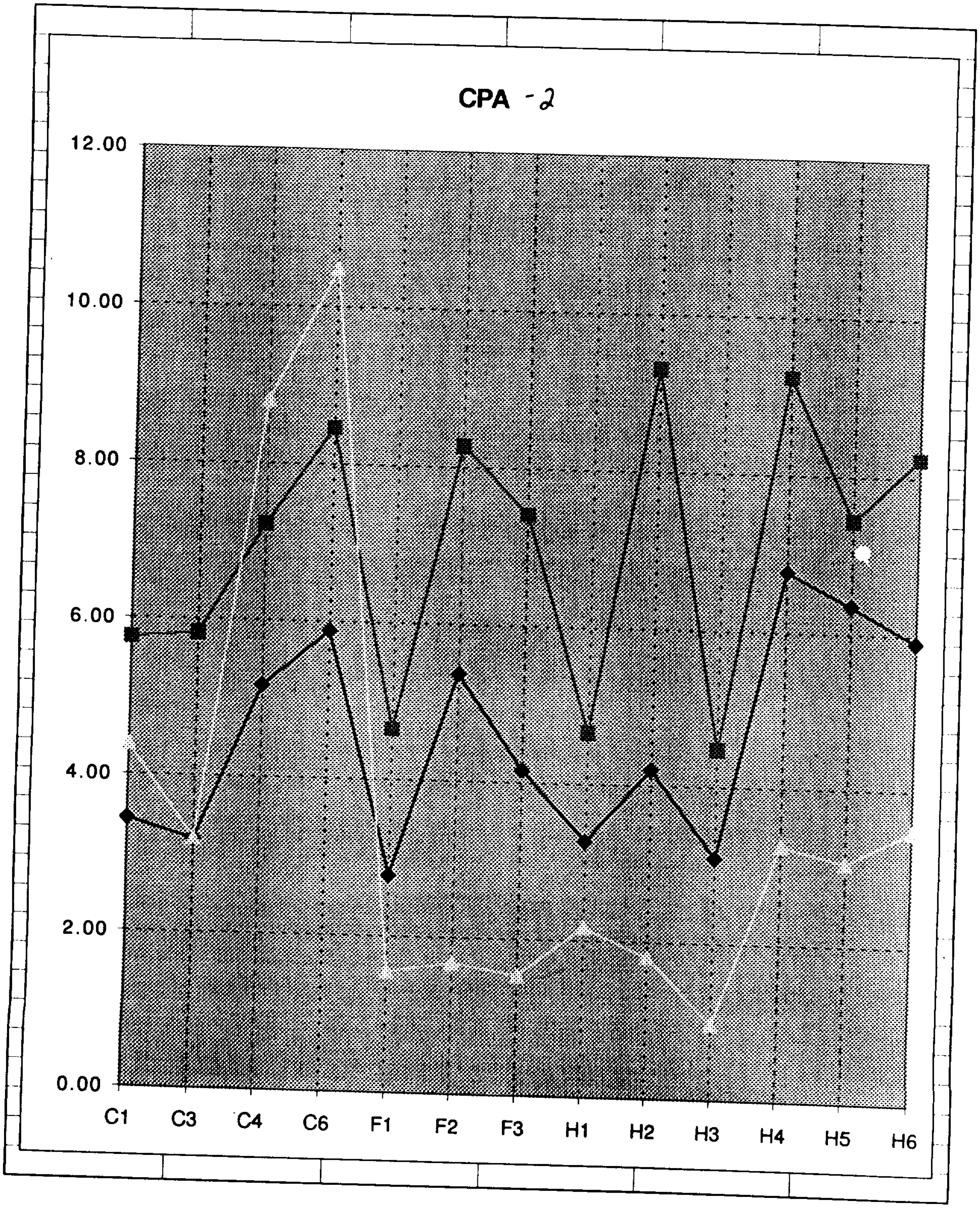
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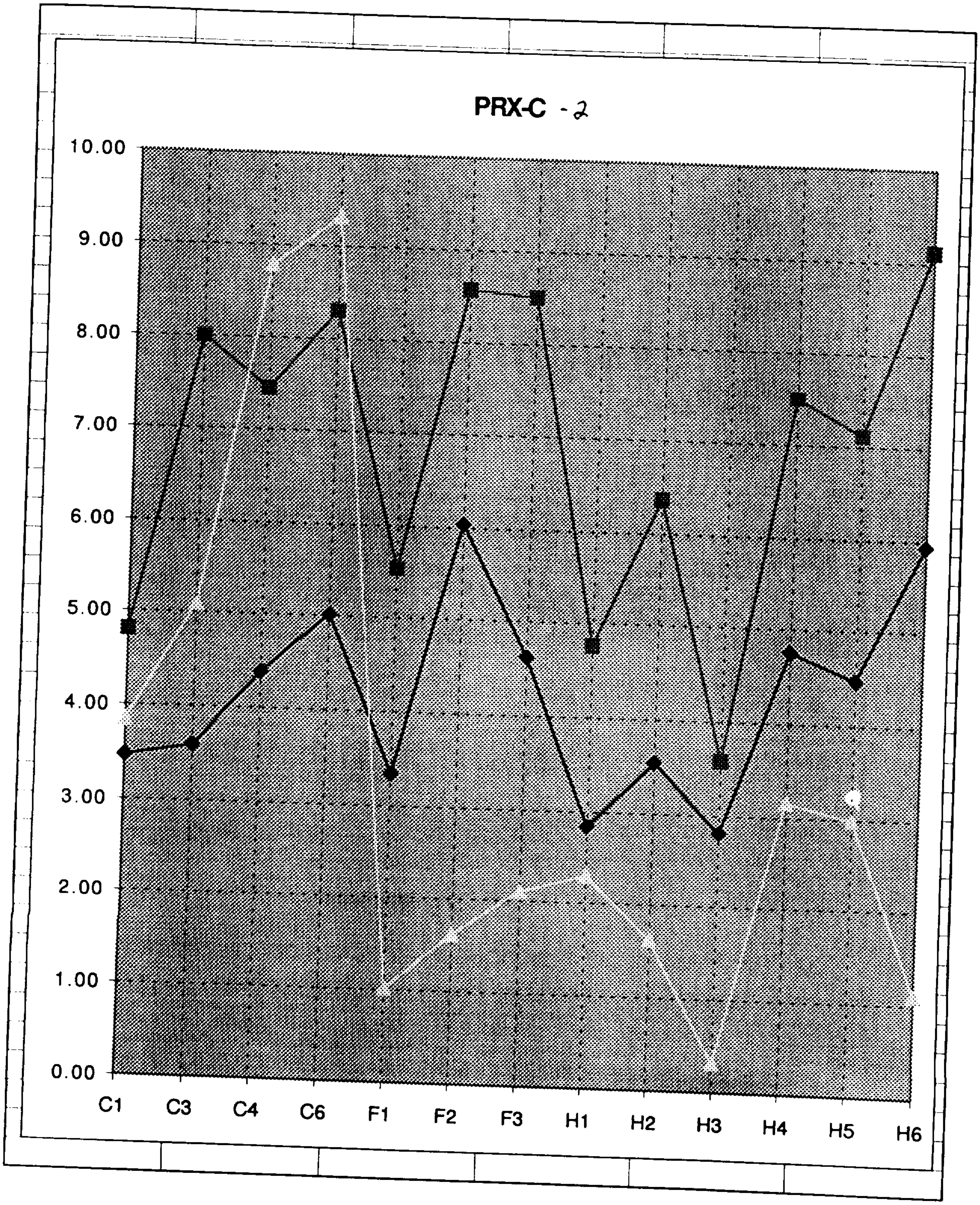
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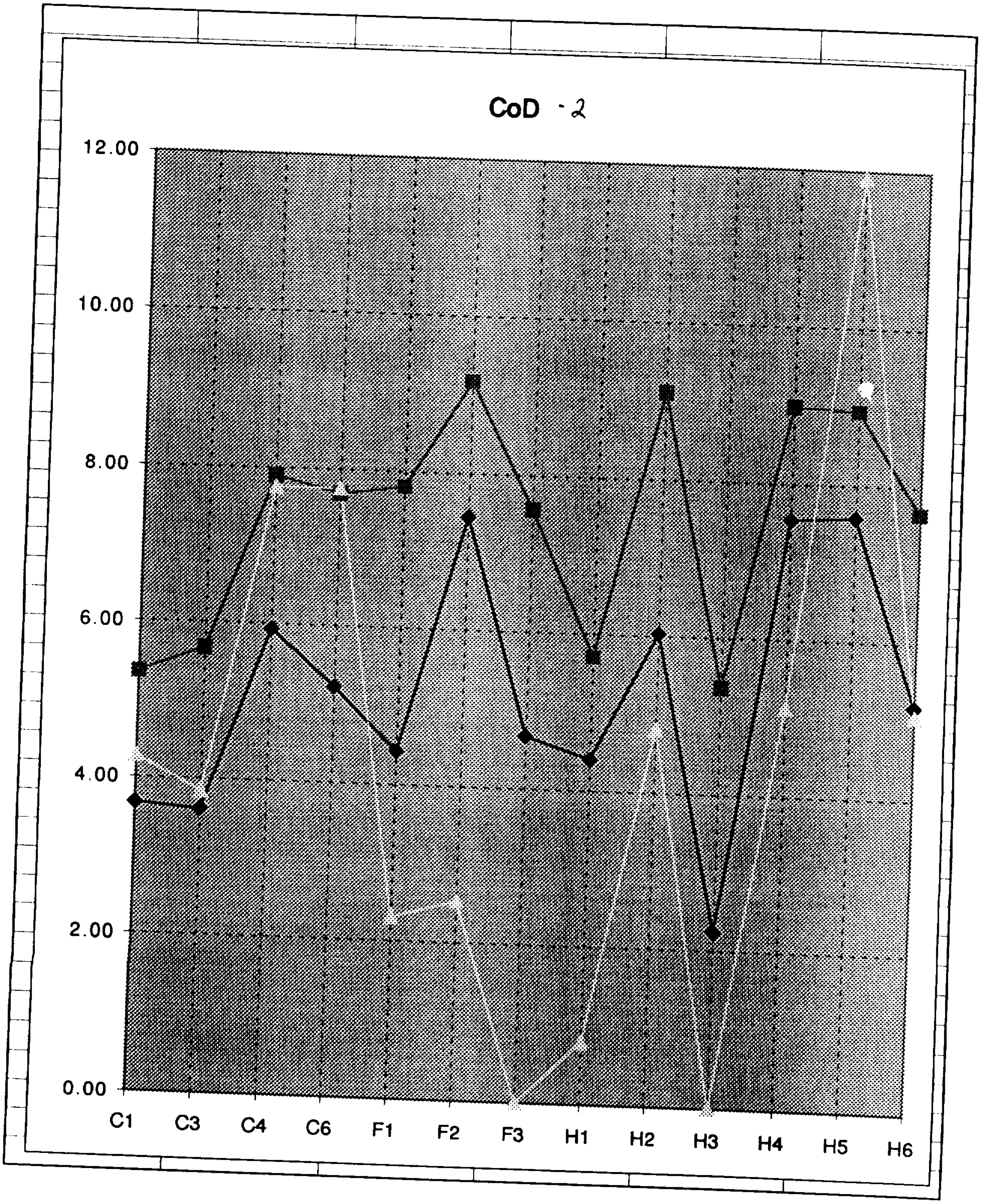
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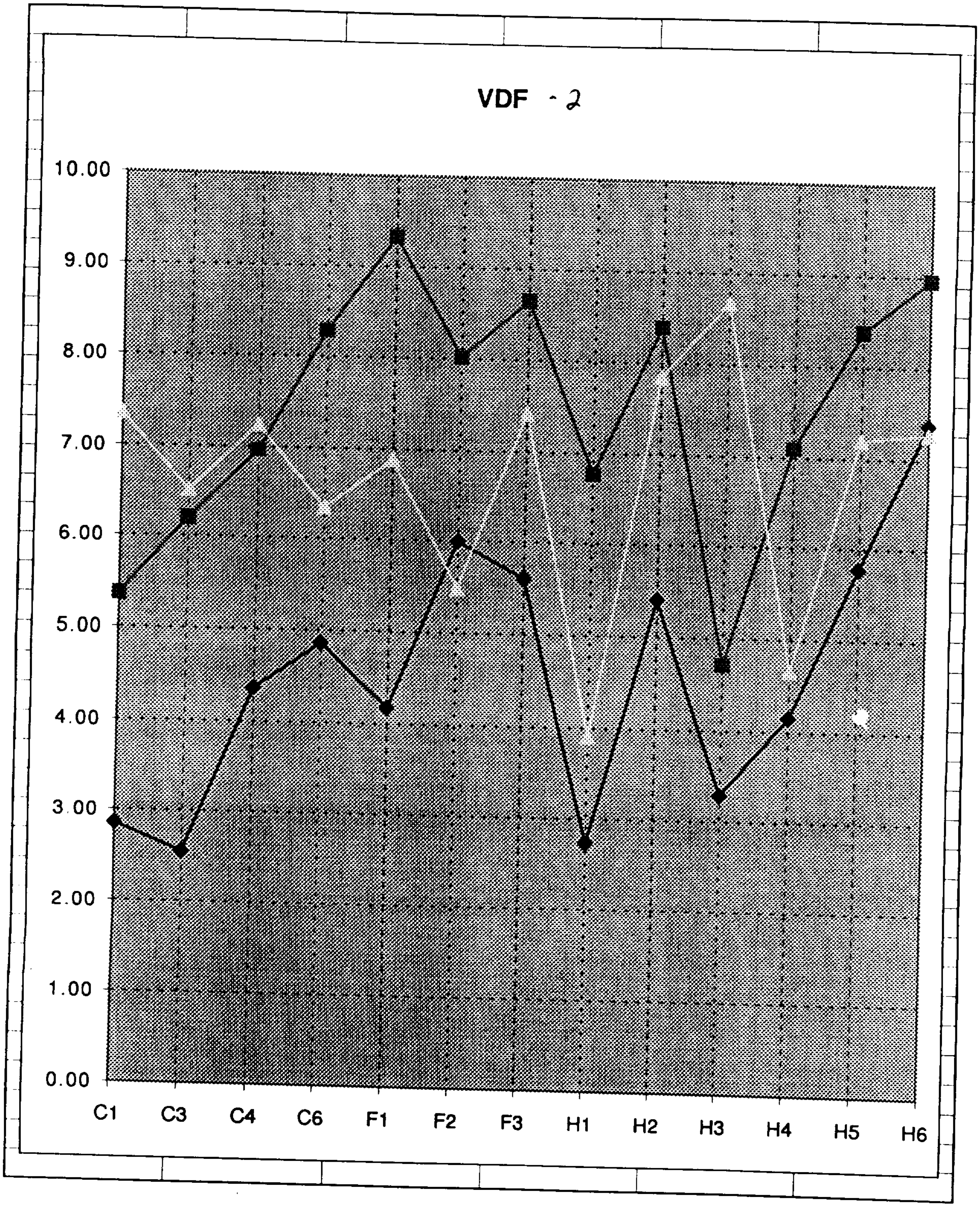
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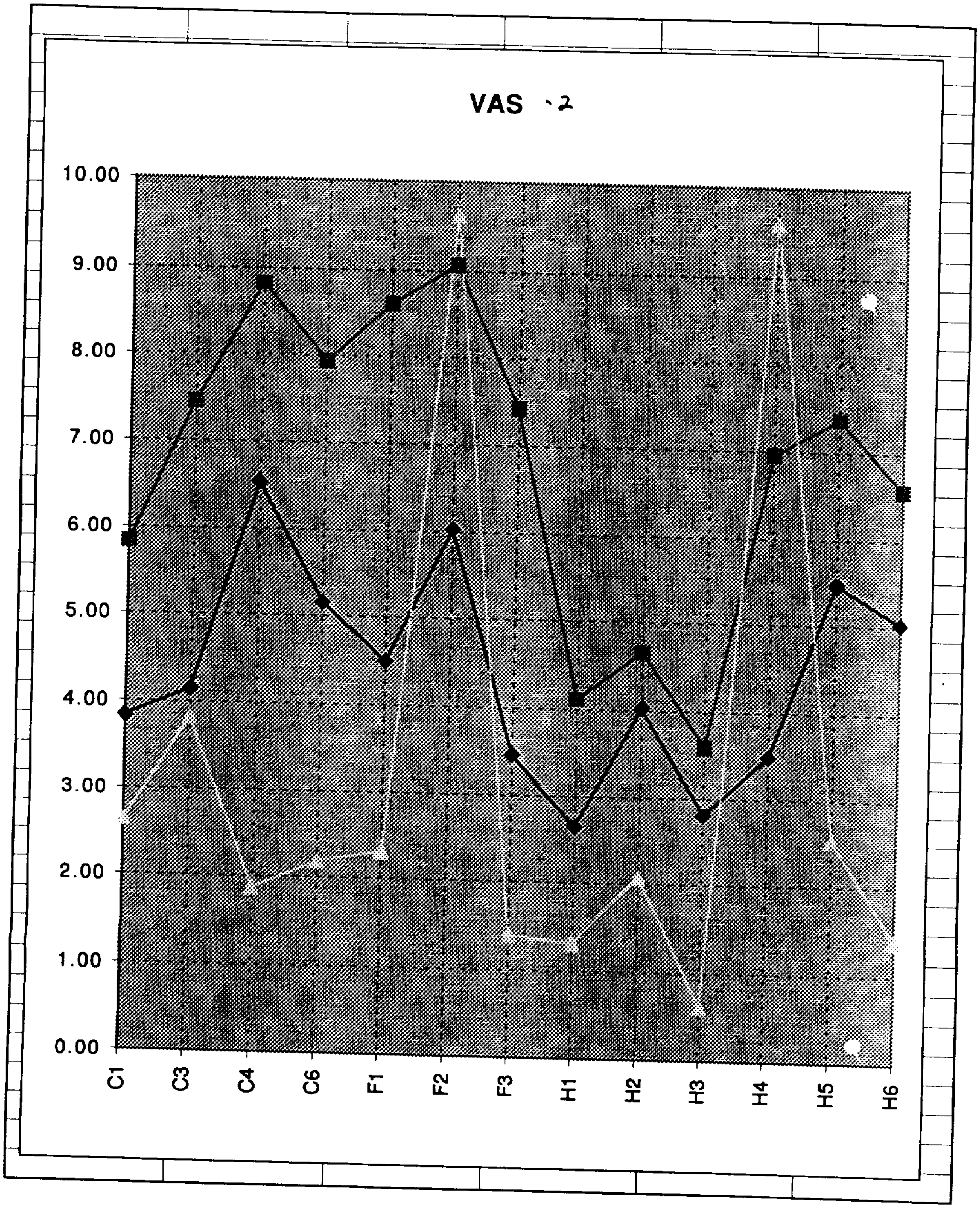
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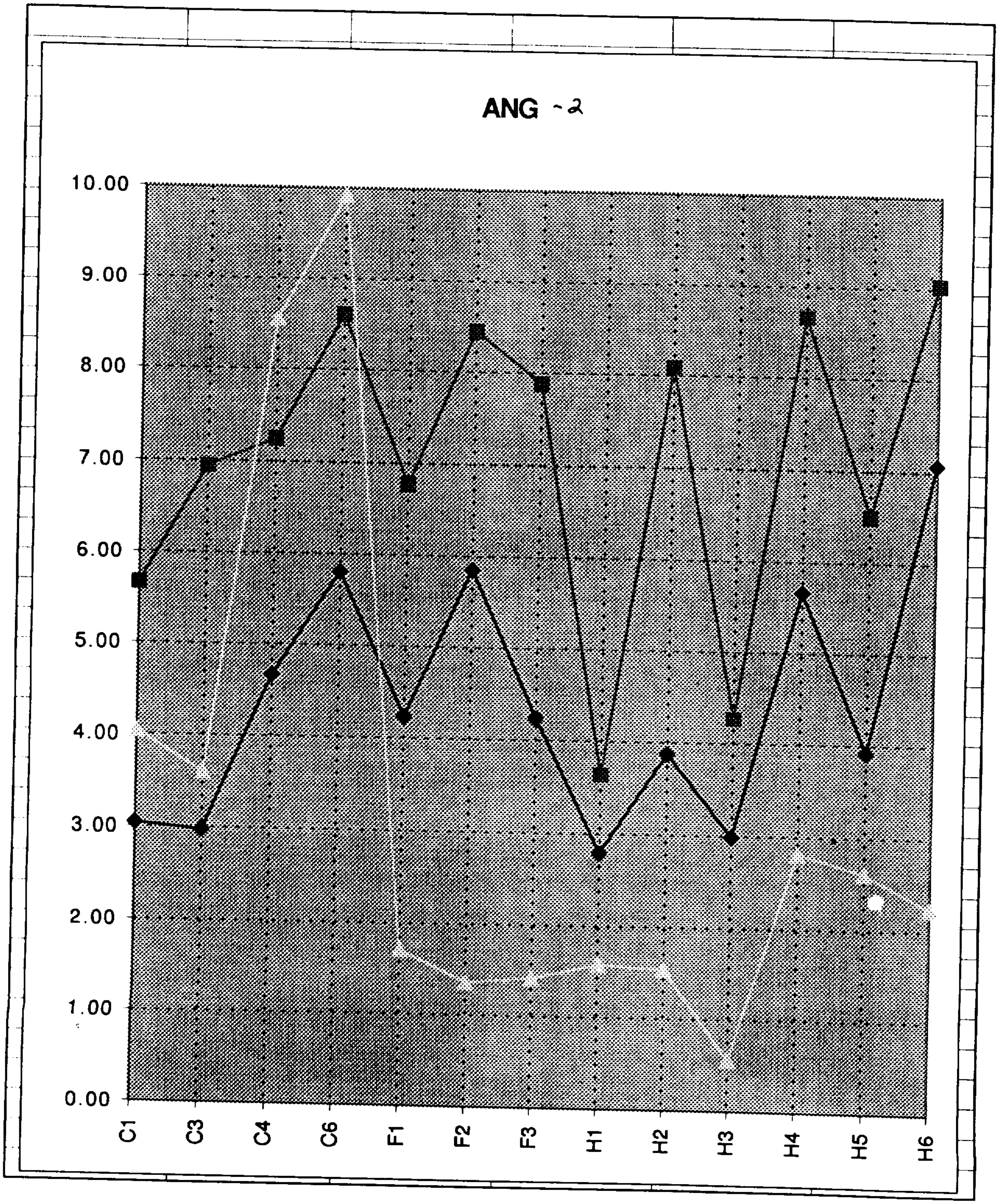
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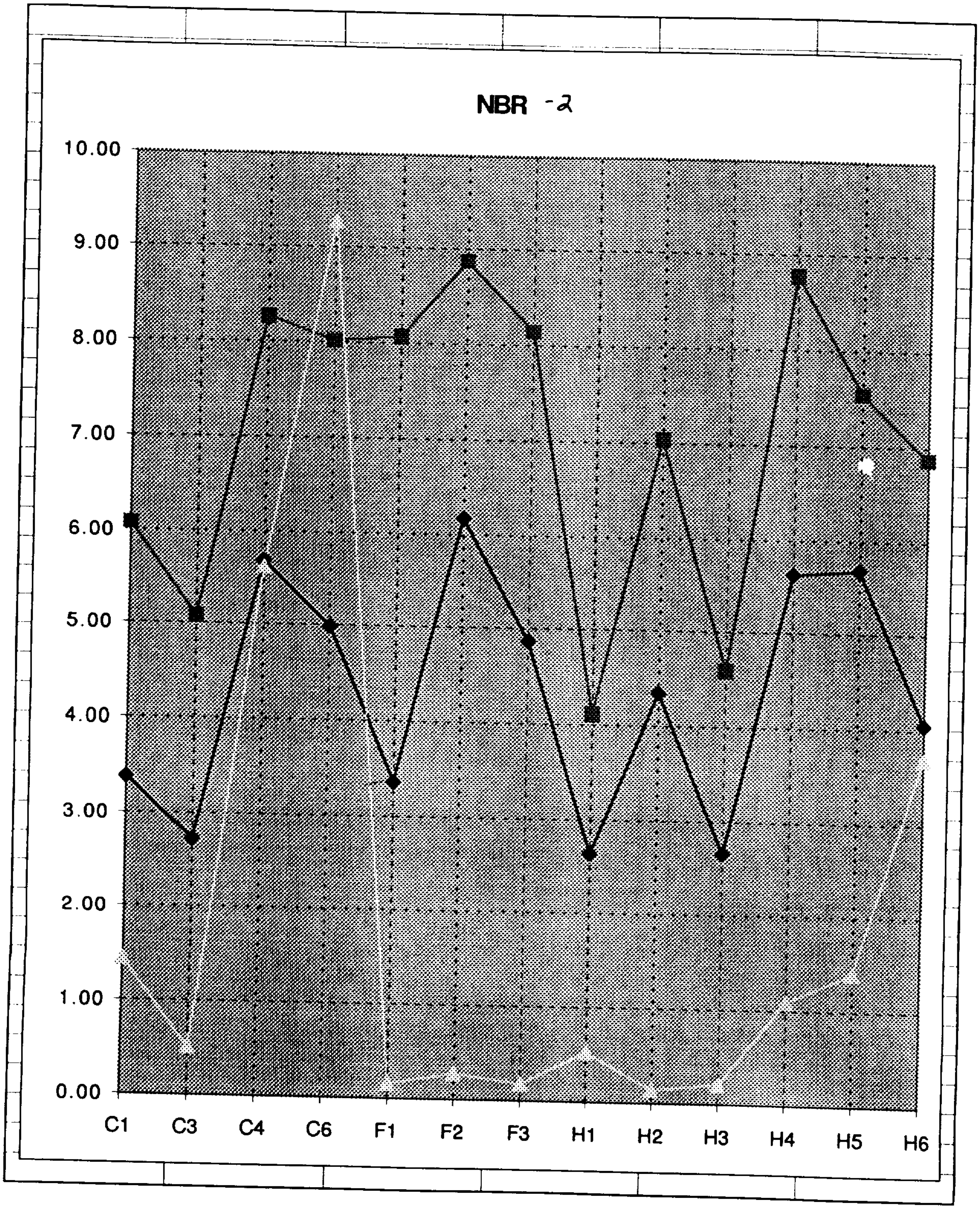

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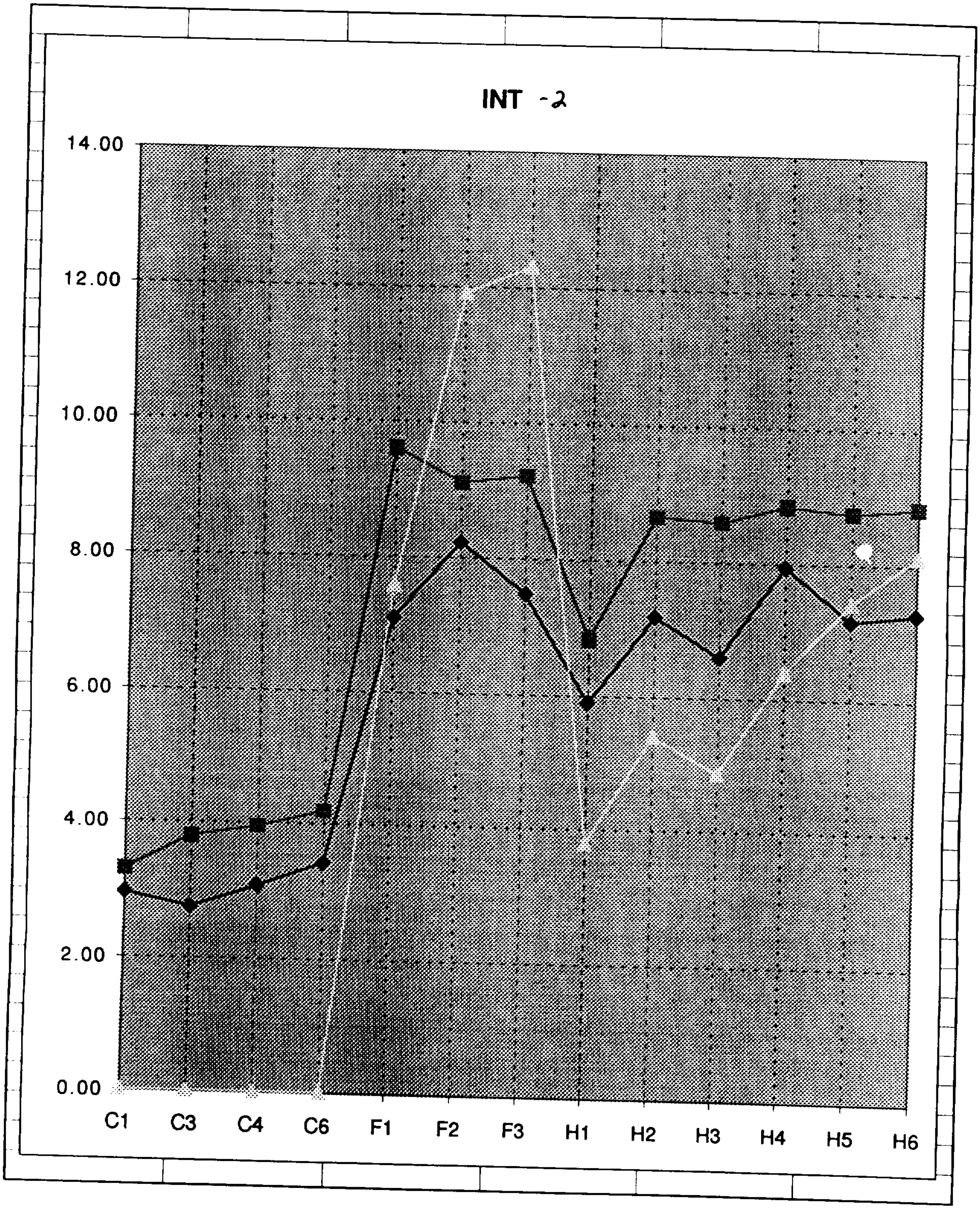
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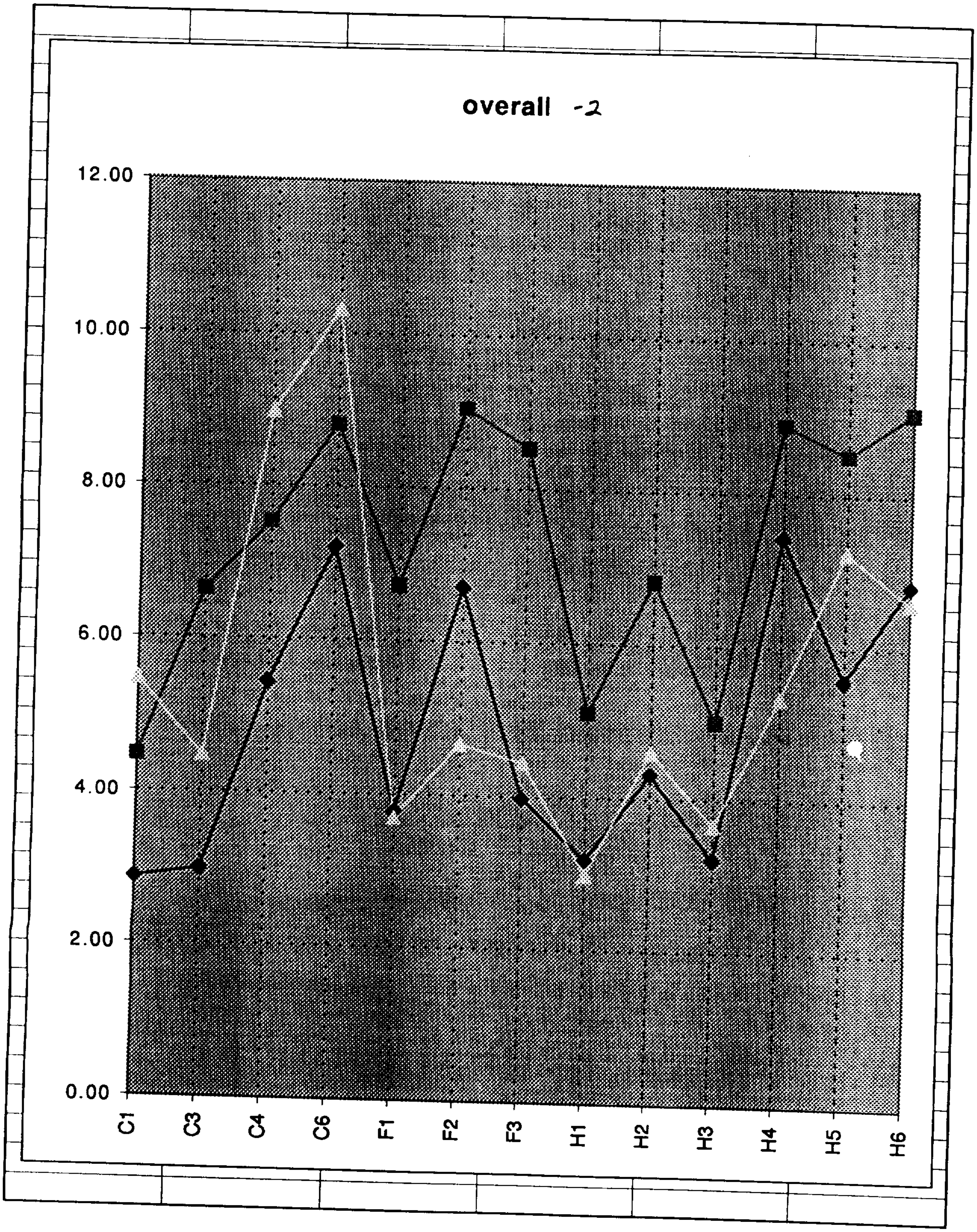
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F2
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H2
H3
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H5
H6

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660 Northstar Court
Boulder, CO 80304

8. PERFORMING ORGANIZATION REPORT NUMBER

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13. ABSTRACT *(Maximum 200 words)*

The work described in this report is done under contract with the National Aeronautics and Space Administration (NASA) to support the Advanced Air Transportation Technology (AATT) program. The goal of this program is to contribute to and accelerate progress in Advanced Air Transportation Technologies. Wyndemere Incorporated is supporting this goal by studying the complexity of the Air Traffic Specialist's role in maintaining the safety of the Air Transportation system. It is envisioned that the implementation of Free Flight may significantly increase the complexity and difficulty of maintaining this safety. Wyndemere Incorporated is researching potential methods to reduce this complexity. This is the final report for the contract.

14. SUBJECT TERMS

Advanced Air Transportation Technology (AATT): Free Flight

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