SPE 66502

# Mapping Air Quality Plumes from Fossil Energy Sources to Assess the Impacts of Secondary Aerosol Development

Thomas J. Rappolt, Tracer Environmental Sciences and Technologies, Inc., Stephen L. Kerrin, Tracer Environmental Sciences, Inc., William Hochheiser, U.S. Department of Energy, Steven Ziman, Chevron Research and Technology Company, Catherine Reheis, Western States Petroleum Association

This paper was prepared for presentation at the SPE/EPA/DOE Exporation and Production Environmental Conference held in San Antonio, Texas, 26-28 February 2001.

## Abstract

In 1998 the U.S. Department of Energy (DOE) embarked upon a feasibility study to research possible ways to sample air quality plumes from fossil energy plumes, especially in their early stages of transport from the source, to better understand the physical dynamics that contribute to plume buoyancy and secondary aerosol deposition. DOE, along with industry partnerships, including the Western States Petroleum Association (WSPA) and Tracer ES&T, Inc., explored concepts of a sampling platform that could easily and safely access plume dynamics to support more accurate modeling and the assessment of fossil energy impacts to ambient air quality. The requirement was to conduct plume monitoring during low and near zero visibility conditions (i.e. fog) which cannot be accomplished using manned flight vehicles or fast moving fixed winged vehicles. The dynamics of the problem require a flexible, slow flying, highly maneuverable sampling platform, from which detailed plume measurements can be made. Hence a remotely piloted airship, under an instrument guidance and control system, offered the best approach. Such a platform, carrying miniaturized sampling/monitoring payloads, provided detailed data concerning the vertical structure of near-term plumes as well as ambient chemistry. This paper presents the various stages of development of Clean Airship 1, a helium filled remotely piloted mini-blimp, planned for use in The California Regional $PM_{10}/PM_{2.5}$ Air Quality Study (CRPAQS) to conduct detailed mapping of specific fossil energy air quality plume structure.

## Introduction

The objective of this study was to provide proof of concept of a new type of sampling platform whereby vertical plume measurements could be accomplished in dense fog conditions at elevations less than 1,000 ft. Tracer ES&T undertook a task to develop a Remotely Piloted Airship for Atmospheric Tracer Sampling (RPATS) based on a commercially-available radio controlled airship. A Global Positioning System (GPS)-based navigation and position reporting system was added and a miniaturized real-time $SF_6$ analyzer was developed in order to provide plume concentration measurements as a function of downwind distance, horizontal location, and height above ground.

The RPATS approach to airborne measurement of plumes is presented in Figure 1. RPATS consists of two main components: the remotely piloted airborne sampling platform and the ground-based control and data logging system. The airship continuously determines its position by means of a GPS receiver and transmits position, flight parameters, and concentration data to the ground station where the pilot uses the information to control the flight path of the airship. The goal is for the pilot to be able to locate an $SF_6$-labeled plume[1,2] from an emissions source and then fly cross-wind through the plume at various altitudes and distances downwind. These three-dimensional data can then be used to determine the dispersion and transport characteristics of the plume as well as the exact height of the plume[3-8].

The RPATS platform was configured to apply this concept to study fossil energy plume dynamics and dispersion under conditions associated with the formation of secondary aerosols and particulates from gaseous emissions. This condition can occur in high humidity and stagnant atmospheres (i.e. wintertime foggy conditions) in the San Joaquin Valley of Central California. Clean Airship I will serve as an important tool in assessing nitrate related impacts from fossil energy sources related to the California Air Resources Board's Central Regional PM10/PM2.5 Air Quality Study (CRPAQS).

The approach used by the Clean Airship I fills an important gap in sampling technology. Clean Aiship I can venture in to conditions and places where normal fixed wing and rotary wing aircraft are unable to perform. Specifically, Clean Airship I offers advantages to traditional airborne platforms which include:

- The ability to sample plumes at lower altitudes and near complex terrain features and urban environments.
- The capability to sample in foggy conditions or under conditions where visibility is poor or near zero.
- Presents virtually zero influence or disturbance to the subject plume structure or region being studied.
- Being a remotely piloted vehicle (RPV), the sampling platform is unencumbered by tethers or any land based lines.

It is important to mention that the Clean Airship I is limited to low wind conditions (less than 12 miles/hr) and ranges of about 2 miles from the base of operation.

## Overview of the RPATS Development Program

Under the initial phase of the RPATS program, Tracer ES&T worked to develop flight readiness status of this unique sampling/monitoring platform concept. A highly maneuverable remotely piloted airship served as the ideal sampling platform. The platform is capable of flight in the lower surface layer of the atmosphere (0 - 1,000 ft.) and follow commands from a ground based station. Since the airship is remotely controlled, it provides adequate safety features and fail-safe systems to prevent accidents due to engine failure and/or radio link failure. The platform/airship provides adequate payload capacity to support systems that provide power, telemetry, plume monitoring, flight performance, and navigation. The current payload capacity for onboard measurement systems is limited to approximately 7-9 pounds.

**Navigation System.** The RPATS required an accurate navigation system depicting the exact position of the airship in time and space. A commercially available GPS receiver provides data regarding position, true heading, and airship ground speed.

**Detection System**. To accomplish virtually real-time plume measurements, the RPATS airship is designed to support a real-time tracer gas monitor to measure ambient concentrations of $SF_6$. Tracer ES&T miniaturized an earlier configuration of the real-time SF6 monitor[13] such that the total weight configuration was less than 2 pounds. The problem of response change due to mass flow variations can now be corrected on the ground as the instrument response and flight parameters emerge from the telemetry receiver. Thus, a small lightweight package provides virtually real-time atmospheric tracer concentration data during airborne operations. Other miniaturized detection devices can be adapted to be used on the airship for low boundary layer studies. Analog signals proportional to measurements can be handled by the on-board telemetry and data management system to accomplish real-time data collection.

**Data Telemetry and Management**. Since the RPATS platform is remotely piloted, a system to telemeter data back to a ground based station was required. High-speed spectrum radio modems were used to provide the link between the airship data system and the ground-based data processor and navigation computer.

In order to fly the airship safely and to take advantage of the positioning accuracy offered by GPS, an accurate display of the position information was required. Maps suitable for computer-based display exist in several forms. Government survey maps (i.e. USGS topographical maps) have been digitized for many areas and are the maps of choice.

The GPS horizontal position data was combined with the digitized map on the ground station computer display. The flight parameters are displayed in instrument panel fashion for pilot reference.

The flight data display consists of a large screen video monitor connected to the ground computer. The majority of the display consists of a map window with

RPATS position indicator. Primary navigation during the flight is by means of this screen. Additional windows provides the pilot with critical GPS derived flight parameters such as ground speed and heading. Secondary parameters such as engine RPM, fuel status, and air temperature is displayed in a less prominent window. Airborne tracer concentration is displayed by means of a bar graph superimposed on the map display and is used to optimize the flight trajectory once the tracer plume is found.

All flight and plume measurement data are stored on magnetic media for later access and analysis.

## General Description of the Flight and Control Components

The Clean Airship I (not procured under the DOE contract) is a commercially available helium-filled low permeability envelope approximately 30 feet in length and 7.5 feet in diameter at mid-envelope. The envelope is constructed of a lightweight specially fabricated low-permeability laminate. Depending on operating altitude, the airship is capable of lifting up to 10 pounds of payload. The need to use lead weights in the nose or tail to balance the airship reduces the practical "bolt-on" payload limit to 7 pounds. A photograph of the flight-ready airship is presented in Figure 2.

A lightweight fiberglass composite gondola is attached to the bottom of the envelope. This gondola contains the radio control components for flight control of the airship, fuel tanks for the twin engines and transverse mounted control bar for thrust vectoring of the engines. Two 1.08 cubic inch displacement alcohol fueled engines are mounted at each end of the control bar. Lightweight composite shrouds surround the engines to protect the envelope from any foreign objects thrown by the propellers and to afford a barrier between ground crew and the propeller arc.

Two vertical and two horizontal fins attached to the aft end of the envelope are constructed with moveable control surfaces (rudder and elevator) for pitch and yaw control. A separate radio control receiver and battery pack is mounted near the fins to provide more efficient and reliable operation than would occur with long control and power leads run from the gondola.

The Clean Airship I is capable of cruising for nearly one hour without fueling at speeds of 10-15 mph. It can reach top speeds of 20 mph with lower fuel efficiency. The airship has no problem in maneuvering to altitudes of 1,000 ft. or more above the ground surface. With proper adjustment to the envelope pressure, the RPATS airship can achieve altitudes in excess of 1,200 ft.

For development purposes, a lightweight epoxy-composite "tray" constructed of Nomex® honeycomb and glass cloth was mounted beneath the gondola to provide a platform for all prototype control, navigation, and data acquisition/telemetry modules. A photograph of this tray is shown in Figure 3. The circuitry mounted on this tray was later redesigned and combined on a single circuit board in order to fit inside the gondola.

A second lightweight composite gondola was fabricated to contain the real-time $SF_6$ instrument or other detectors of choice. This enclosure was mounted forward of the main gondola with the sample inlet facing forward. This position places the inlet in the most undisturbed airflow available without having an unacceptably long sample tube originating at the nose of the airship. The $SF_6$ instrument and hydrogen gas supply are shown in Figure 4.

The ground-based components of RPATS consist of a means to control the flight path of the airship and a computer which communicates with the navigation/sensing modules aboard the airship via a radio telemetry link.

Flight control of the airship is accomplished by means of a commercially available radio-control system. As configured for prototype trials, the operational range for the system under test is approximately two miles.

The Flight Director computer consists of a custom software package and a radio frequency (RF) modem. The software continuously interrogates the airborne data package via the RF modem and displays navigation, tracer concentration, and operational parameters on a large video display.

**Description of Airborne Navigation, Control and Sensing Components.** Successful operation of RPATS under instrument flight conditions requires that accurate, reliable and timely navigation and operational data be available to the pilot. While these parameters are easily measured, the 6 to 7 pound weight limit for the entire navigation, sensing, power, and control systems presented a significant design and construction challenge. Custom designed electronics, component miniaturization, and a return to very basic instrument design allowed realization of all development goals. Integration of the separate modular components in the flight package is shown schematically in Figure 5. A photograph of the navigation, control, and telemetry hardware on their mounting tray is present in Figure 3.

**GPS Navigation**. The widespread use of the Global Positioning System (GPS) for civilian use has generated equipment and techniques for very accurate position measurement. GPS satellites transmit two different codes, one for military use, and a second which is available for civilian use. At the time RPATS was proposed, the use of differential corrected GPS was advocated for position accuracy to less than 10 meters. The use of differential correction was necessary due to the United States military's degradation of the GPS data available to civilians by introducing Selective Availability (SA) to degrade positional accuracy to as much as 100 meters. Differential correction allows accuracies of 3-10 meters to be realized in spite of SA. On May 1, 2000, SA was eliminated from the civilian code and, thus, differential correction is not necessary unless SA is reintroduced. A Lassen LP® GPS receiver manufactured by Trimble Navigation Ltd. was selected due to its size, weight, low power consumption, and direct interface for communication and differential correction. Upon interrogation, the device transmits a data string via a serial communications port. This data string contains current latitude, longitude, ground track (course), and ground speed. While altitude information is available, it is not sufficiently accurate for use in RPATS except under special circumstances of satellite availability and, hence, was not used. The serial input/output of the receiver was connected to an addressable data multiplexer (described in a later section) for transmission via RF modem to the ground station.

**Altitude Measurement**. To provide accurate altitude information for the flight package, an electronic altimeter was designed around a solid state pressure transducer. The range of the altimeter was -200 to 5000 feet and the accuracy was ±7 feet. The altimeter module was connected to a data acquisition system (DAS) module for digitizing and transmission. This module will be described in a later section.

**Heading, Attitude and Temperature**. Successfully piloting the airship under instrument conditions also requires that flight attitude information be available. A TCM2 Electronic Compass Module from Precision Navigation, Inc. provides magnetic compass heading. The module also contains inclinometers on two axes to provide pitch and roll information as well as a temperature sensor. These parameters are transmitted via a serial output port to the addressable data multiplexer.

Although course (ground track) information is available from the GPS data, compass heading allows the pilot to determine whether the airship requires yaw correction to maintain course. If yawing is required to maintain course, either a cross-wind is present or an engine is not working properly and further scrutiny is required by the pilot as an engine-out condition dictates a return to base per our operating procedures.

Pitch angle data is necessary during all phases of flight. Ascent and descent rates are determined, in part, by pitch angle and must be monitored during such maneuvering. A requirement for large positive pitch angle (up-elevator) to maintain altitude in cruise indicates loss of buoyancy or loss of engine power. Either of these conditions require a return to base for remedy.

While roll angle data is available from the module, the inherent roll stability of the airship relegates this information to "just for curiosity" status.

**Data Acquisition**. While the GPS and compass modules, used for bidirectional communication, possess serial data communication ports, the electronic altimeter and $SF_6$ instrument have analog outputs. These analog signals require conversion to digital format prior to being telemetered to the ground station.

A multifunction data acquisition system (DAS) board was designed and fabricated. This board provides four channels of 10-bit analog to digital (A/D) conversion, two 12-bit A/D channels, and digital control lines. A serial data input/output (I/O) interface provides multiplexed ports for on-board serial devices and a port for communication with the RF modem.

The altimeter and $SF_6$ instrument outputs are connected to the two 12-bit channels to provide maximum resolution. The 8-bit channels were used to monitor operational parameters such as power supply status.

**Telemetry**.

RF Industries, Inc. Model SS9600 spread spectrum radio frequency modems provided each end of the telemetry link during initial development. These units operate at 9600 baud in the license-free portion of the 2.5 GHz industrial and medical frequency allocation. Reliable communication is assured by the frequency-hopping nature of the devices utilizing spread spectrum techniques, wherein data is only exchanged when both units experience a clear channel of the hundreds of channels available. The communication range for these units is approximately 2 miles.

These 9600 baud RF modems were replaced in the current version by Free Wave Technologies data transceivers which have a maximum data transfer rate of 115,000 baud.

**Real-time $SF_6$ Instrument.** The real-time $SF_6$ instrument is based on a design first appearing in the mid-1976[13]. While later refinements of this design yielded a more stable and sensitive instrument[14], the size, weight, and power requirements preclude the "improved" version from consideration.

A schematic of the $SF_6$ instrument is presented in Figure 6 and a photograph in Figure 4 A low-power pump delivers sampled air to the inlet of a catalytic reactor where it is mixed with a small amount of hydrogen. This results in exothermic conversion of the oxygen in the sample air to water as steam. The sample flow emerging from the reactor now contains only steam, nitrogen and any $SF_6$ present. The steam is allowed to condense as it cools and gross water is removed through a water-permeable hydrostatic barrier. The partially dried sample then passes through a secondary drier consisting of permaselective membrane tubing surrounded by a desiccant bed. The thoroughly dried sample then enters the detector whose output is proportional to $SF_6$ concentration in the sample stream. A miniaturized electrometer amplifier conditions and amplifies the detector signal and routes it to the DAS for digitization and transmission in raw form to the ground.

The hydrogen supply for the instrument was contained in three lightweight drawn-aluminum cylinders, similar to aerosol spray cans. These cylinders were rated for pressures up to 150 PSI and were pressurized to 125 PSI with hydrogen to provide sufficient gas for 4 hours of operation. While it would be more desirable to use one cylinder at higher pressure such a cylinder would need to be stronger and, thus, heavier. Additionally, operation at lower pressure allows the use of smaller and lighter valves and flow control hardware.

No effort was made, in this phase of development, to optimize instrument sensitivity. As flown for demonstration flights, the response range of the instrument was from approximately 75 parts-per-trillion (ppt) to more than 5000 ppt.

**Power**. A major consideration in obtaining a lightweight flight package is battery type and capacity. The selection of batteries was postponed until all power consuming devices had been built, tested, and integrated. Peak and average power consumption based on a minimum 3-hour operation period dictated the battery capacity requirements. The resulting ampere-hour requirement quickly eliminated nickel-cadmium (NiCad) batteries on the basis of weight. Nickel metal hydride (NiMH) batteries were selected based on their high ampere-hour capacity and light weight. Seven NiMH cells were assembled into a pack yielding a nominal voltage of 8.4 volts with a 3.7 ampere-hour capacity at half the size and weight of a comparable NiCad pack.

**Ground Control and Flight Director.** Pilot control of the RPATS airship from the ground is accomplished using a commercially available 10-channel radio-control transmitter. This unit is physically separate from the Flight Director computer and electronically isolated from the navigation and sensing components of the system. Two 2-axis control sticks provide throttle/rudder and elevator/rudder control. Additional switches and controls allow for trimming the airship flight characteristics and switching the thrust vectoring controls between maneuvering and normal flight modes.

The RPATS Flight Director consists of a common PC and high resolution display. The PC communicates with the RPATS airborne package via a radio modem identical to that previously described.

The Flight Director presents all operational flight data, position data, and relative tracer concentration in an easily interpreted visual display. A screen capture of an early version of the Flight Director during a training and test session is presented in Figure 7.

The flight situation indicator in the upper right corner of the display indicates the airship attitude in pitch and roll as well as the compass heading corrected for magnetic deviation. Below the situation indicator the pressure altitude above sea level (MSL) and the height above takeoff (AGL) may be seen. It should be noted that the AGL indication does not compensate for terrain variations above or below field altitude. The vertical speed indicator (VSI) is not implemented in this version. Below the VSI may be seen the air temperature and power supply voltage indicators.

The majority of the display is occupied by the moving map. Above the moving map may be seen the ground speed and UTM position coordinates. These are derived from the GPS data stream.

The moving map display consists of a digitized 7.5 minute USGS map for the area of interest. The mapping software allows for multiple maps to be seamlessly joined by the computer to provide large area coverage. Centered on the map is an airship icon whose orientation is determined by deviation-corrected magnetic compass heading. The line projecting forward from the icon is actual course as determined by the GPS receiver. The airship icon is always centered in the display and the map “moves” underneath. Additionally, zoom in and zoom out features are available to the pilot. The display represented here represents an area approximately 1 km square. A bar graph above the airship icon indicates relative $SF_6$ concentration. In this screen image, the tracer release point and estimated plume centerline are indicated, respectively, by a small cross and line passing through the airship icon. These parameters do not appear during flight tasks, but were graphically added for discussion purposes. Note that tracer has been detected as the airship passes through the centerline. Since the real-time $SF_6$ instrument has a response delay time of 4-5 seconds, the indicated concentration actually occurred at a point behind the airship. This skewing can be adjusted during data reduction.

In addition to displaying the flight and sensor parameters, the Flight Director continuously writes a data file containing position, altitude, time, tracer concentration, and temperature. This data is also available via a serial communications port allowing the data to be captured by a second computer without disturbing the flight crew. This data may then be viewed in the field so that adjustments to the release or sampling pattern can be made in order to maximize data capture.

Three-dimensional plots of relative $SF_6$ concentration taken during one test flight are presented in Figures 3.7 and 3.8. Please note that these presentations are from non-calibrated data, therefore, no units are provided. The figures simply indicate that a plume was detected by the RPATS platform and conveyed qualitatively for demonstration purposes. Using RPATS in the CRPAQS program would require quantitative data that is calibrated and verified, whereby, providing discernable measurements.

## Utilizing Clean Airship I in the CRPAQS

The California Regional $PM_{10}/PM_{2.5}$ Air Quality Study (CRPAQS) intends to improve scientific understanding of excessive suspended particulate matter (PM) levels in the central California region[15]. The study will help provide insight on how regulators will proceed to reduce PM exposure to populations in the San Joaquin Valley and other central California regions. As an integrated effort, the CRPAQS includes comprehensive air quality and meteorological measurements, emissions characterizations, data analysis, and air quality modeling. The CRPAQS activities are complementary to other long-term monitoring and research activities conducted by the U.S. Environmental Protection Agency (EPA), the California Air Resources Board (ARB) and numerous local air quality districts in the region.

The CRPAQS program goal is to “provide additional and more comprehensive information than is currently available to explain the nature and causes of particulate concentrations...in and around central California”[15]. This programmatic information will be used to adopt or modify control strategies for reducing PM in certain regions of central California. With this goal in mind, specific field study objectives were adopted. A portion of these objectives include[15]:

- Characterize the source zones of influence and quantify source contributions to community exposure for PM chemical compounds, including particulates that are directly emitted and those that form from directly emitted gases.

- Quantify source contributions to secondary aerosols, identify limiting precursors, and assess the extent to which reductions in nitrogen oxides, ammonia, sulfur oxides, and volatile organic compounds would be effective in reducing PM concentrations.

- Refine conceptual models that explain the causes of elevated PM concentrations and interactions between emissions, meteorology, and ambient PM concentrations.

- Evaluate and improve the performance of emissions, meteorological, and air quality simulations. Apply simulation methods to estimate PM concentrations at receptor sites and to test potential emissions reduction strategies.

Clean Airship I provides an excellent opportunity to study the plume characteristics of fossil energy sources, particularly when operating under the adverse winter-time conditions experienced in the San Joaquin Valley.

Specifically, under CRPAQS, the airship platform will be used to precisely map plume structure and height as it pertains to fossil energy sources. Scientists associated with the CRPAQS believe that secondary ammonium nitrate is generated by both surface sources and sources which release elevated plumes of oxides of nitrogen, following oxidation and reaction with ambient ammonia during stagnant wintertime fog episodes. Data from the Clean Airship I will define the extent of near-term plume characteristics exhibited by fossil energy plumes. This information would have significant influence on accurately projecting the impacts these sources have on downwind regions.

The data from the airship, as it applies to the CRPAQS, will help the regulators better understand the mechanisms by which plumes from elevated sources are entrained into the mixed layer, and the timing of entrainment. Use of an inert tracer does not allow one to follow the conversion of NOx to nitric acid, and the reaction of nitric acid with ammonia. However, the information gained from the tracer measurements should allow a more realistic representation of the meteorological processes which result in high ground level concentrations of ammonium nitrate. In particular, incorporation of this information into a photochemical modeling system should allow a better understanding of whether and to what extent oil field combustion sources, which emit NOx above the surface via elevated plumes, contribute to ground level ammonium nitrate concentrations. This information should contribute to effective control strategies to reduce ammonium nitrate.

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Figures for SPE Paper No.:66502

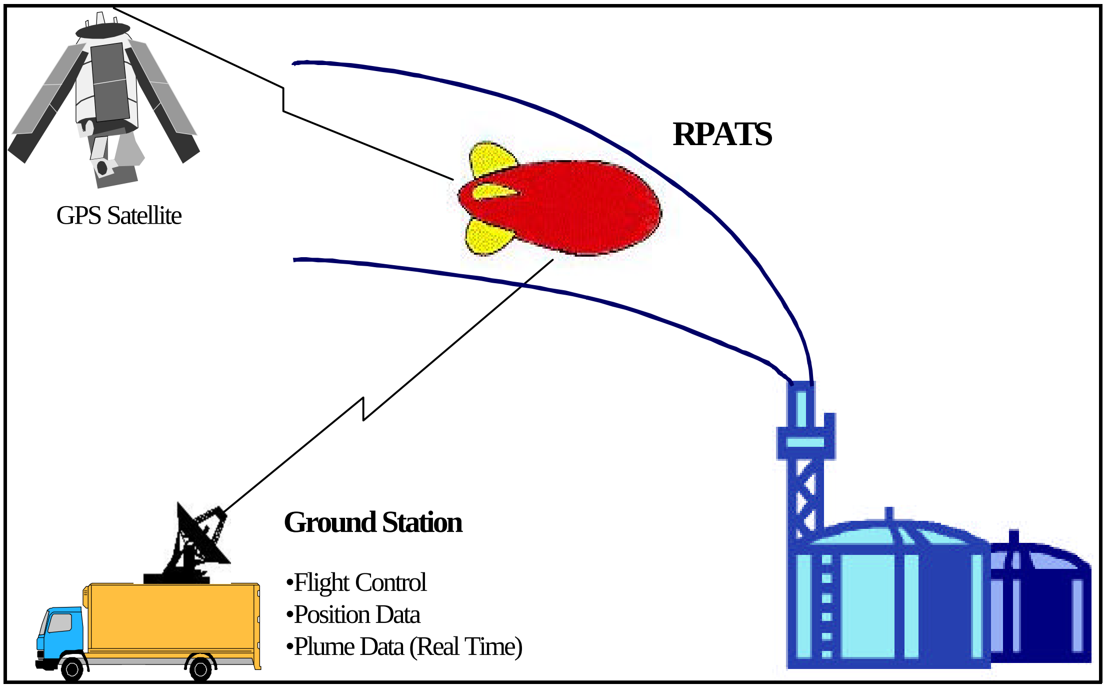


**Figure 1. Concept Diagram of the RPATS Air Sampling Platform**

**Figure 2.** Clean Airship 1 in Flight Ready Status.

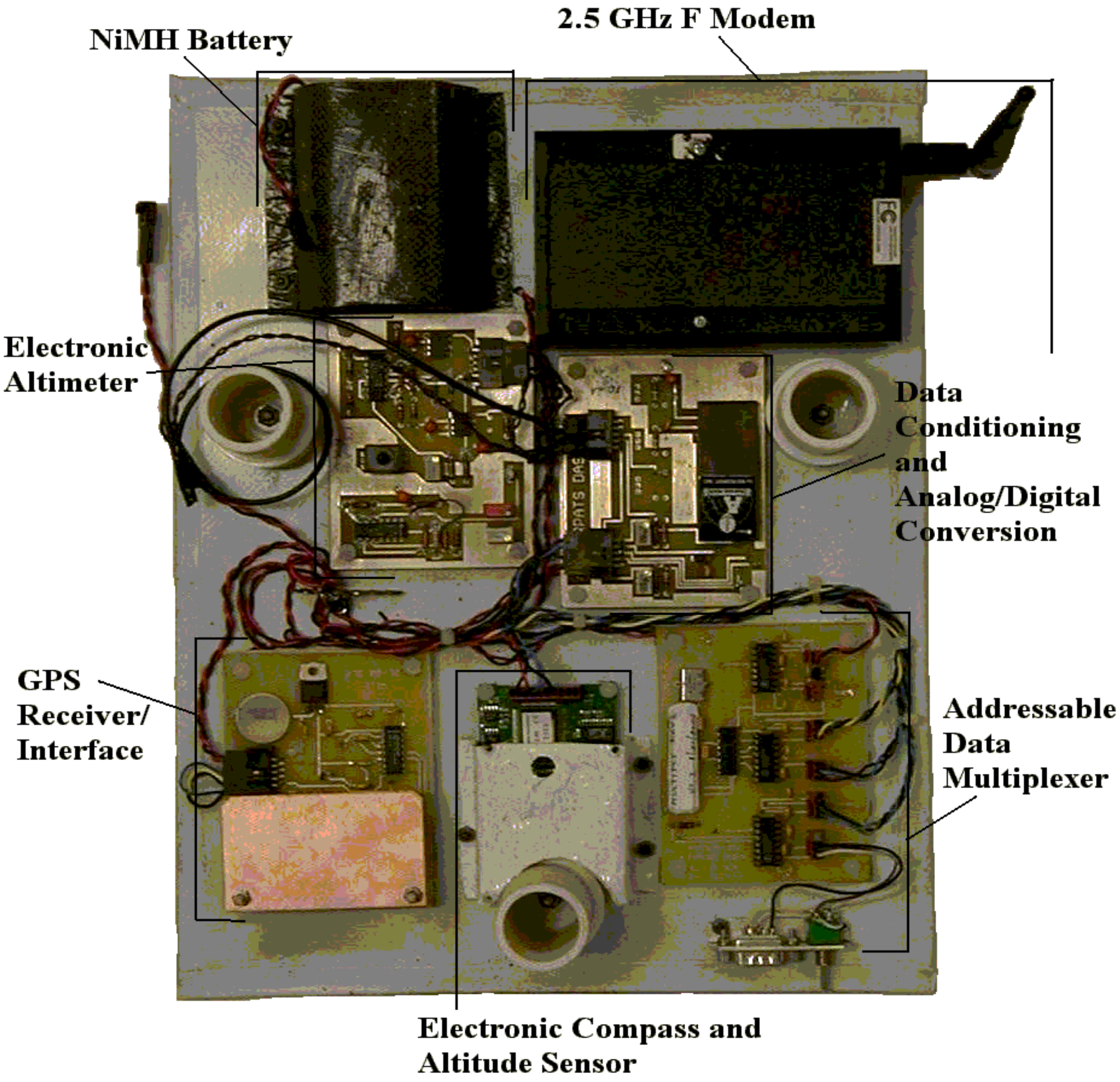


**Figure 3.** RPATS Airborne Navigation, Control and Telemetry Components.

**Figure 4.** Photograph of Real-time $SF_6$ Instrument

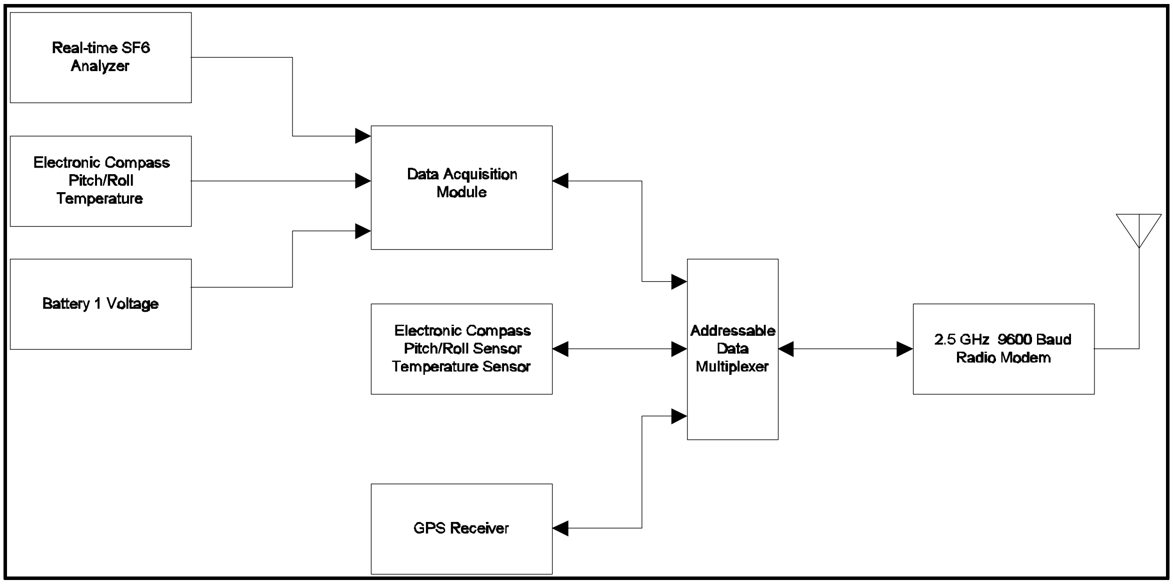


**Figure 5.** Block Diagram of RPATS Navigation, Sensing, and Telemetry System

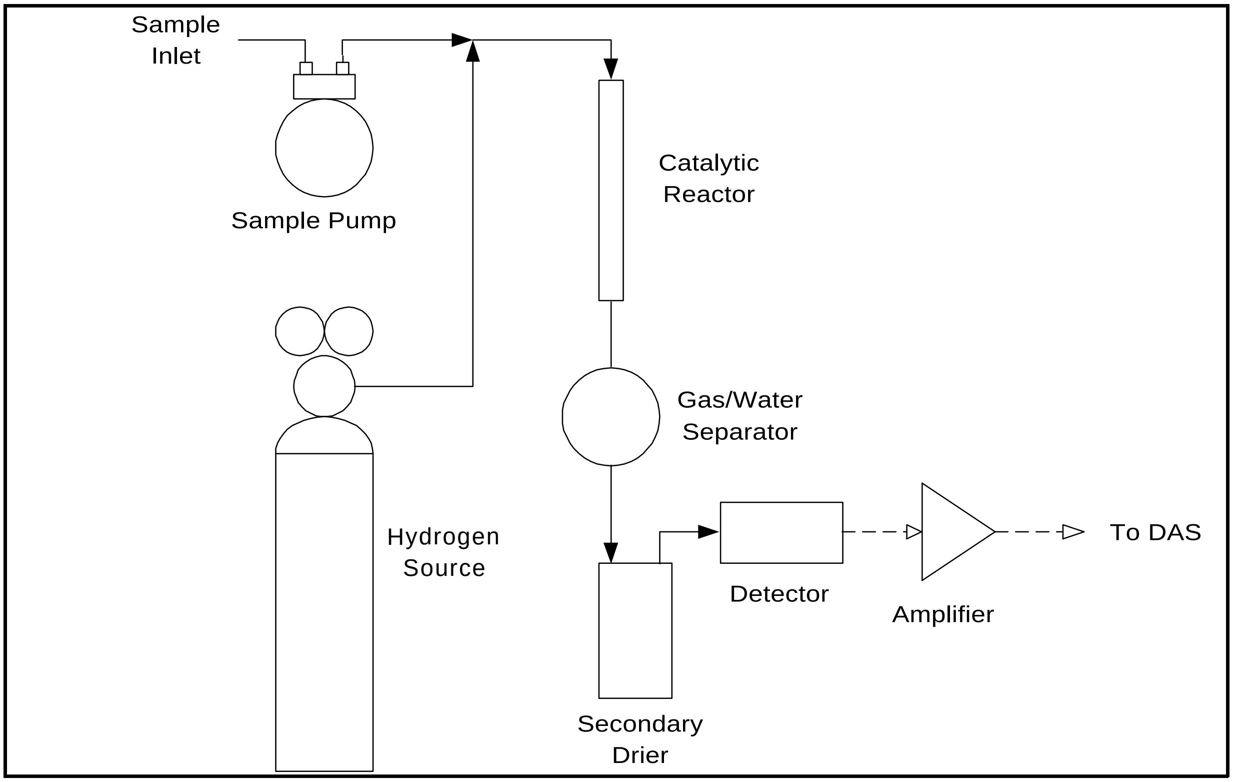
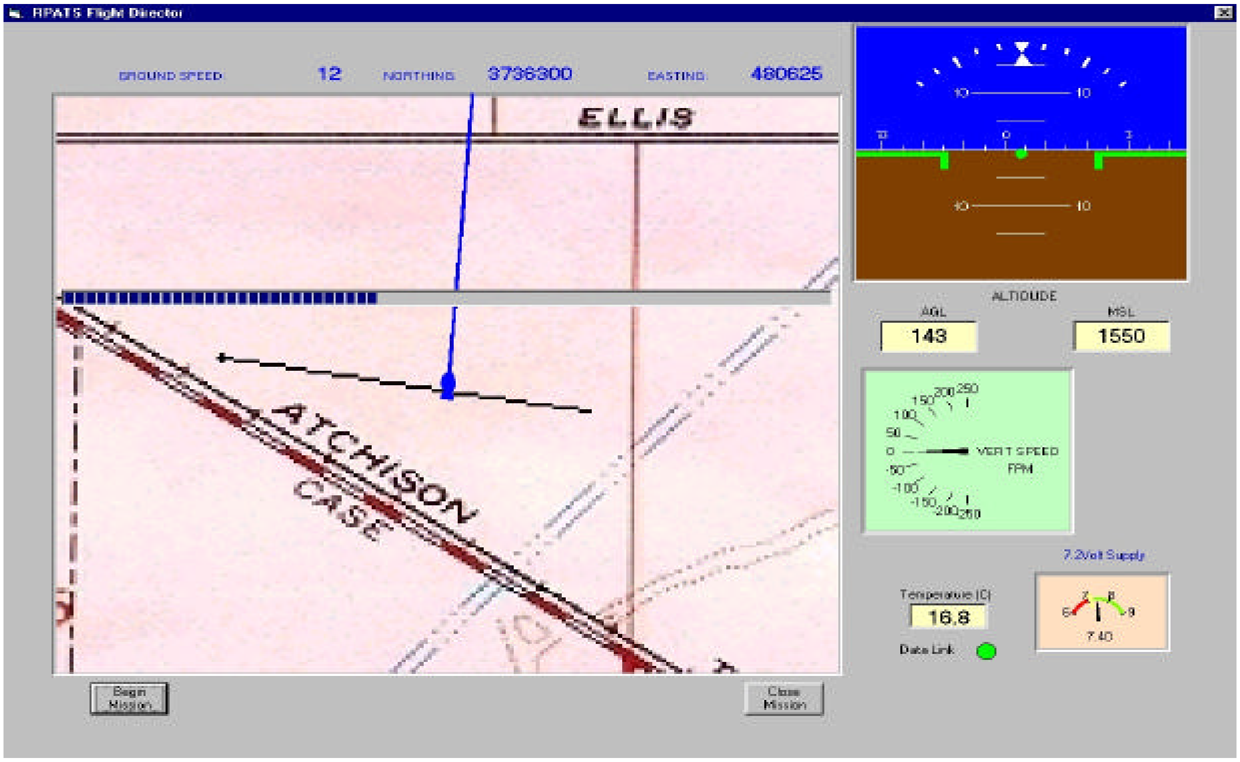


**Figure 6.** Block Diagram of Real-time $SF_6$ Instrument.



GROUND SPEED 12
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EASTING 460625
AGL 143
MSL 1550
Temperature (C) 16.8
7.2Volt Supply 7.40

**Figure 7.** RPATS Flight Director Display

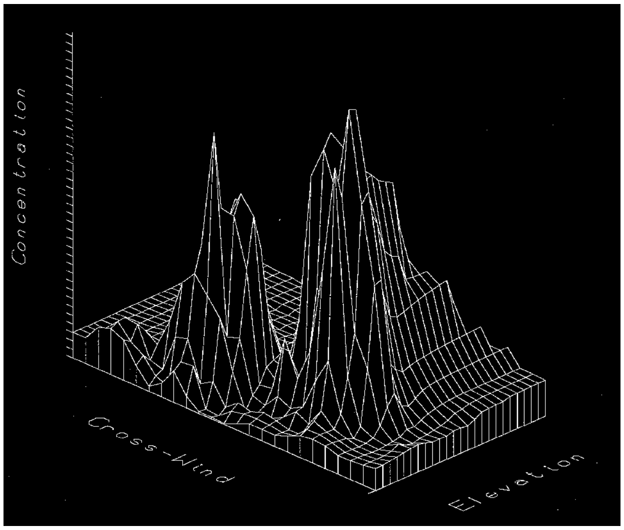

**Figure 8.** Three-Dimensional Plot of $SF_6$ Concentration Showing Elevation and Cross-Wind Direction.

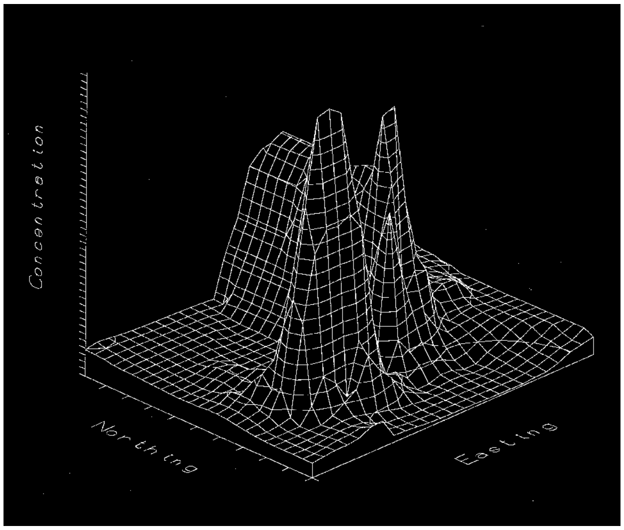

**Figure 9.** Three-Dimensional Plot of $SF_6$ Concentration Showing the Easting (x) and Northing (y) Locations.