Chapter 4

Navigation Aspects of Airborne COSPEC Determinations of Volcanic Sulphur Dioxide Flux

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1. INTRODUCTION

Volcanic sulphur dioxide flux measurements with the COSPEC correlation spectrometer are a routine and important part of volcano monitoring and research. Traverses, flown under the plume, utilizing an aircraft mounted COSPEC, provide a safe, quick and accurate method for determining SO_2 flux. The accuracy is a natural consequence of the aircraft's abilities to place the COSPEC on perpendicular traverses (or traverses at a known angle to the plume) at the appropriate distance downwind and at a short optical path-length below the plume. Perhaps most significantly, the aircraft can be used as a tool to accurately determine the wind velocity at the plume altitude(s), which is a major source of error in SO_2 flux data.

A number of papers have discussed airborne determinations of SO_2 flux from volcanoes (e.g., Stoiber and Jepsen, 1973; Casadevall et al., 1981; Stoiber et al., 1983; Sutton et al., 1992; Schaefer et al., 1997). This paper adds to the literature by describing specific methods that can be used in a wide variety of circumstances to produce accurate results. The material is comprehensible by both geoscientists and pilots and is intended to be used as a resource when planning airborne COSPEC operations. It is primarily directed at infrequent users (due to limitations of budgets or volcanic activity) of COSPEC in aircraft, and provides the necessary information to obtain good navigation data, and therefore good flux data from any fixed-wing aircraft. Those researchers who have access to research aircraft or perform routine monitoring will find much of what is discussed already being performed by themselves and/or their pilots. There are too many variables (e.g., wind shear, ash/aerosol fallout and concentration, visibility, plume height above ground, etc.) in each specific COSPEC mission to discuss every possible scenario, but the methods described herein can be adapted to fit most circumstances. Many of these variables can affect safety and/or data quality/quantity and therefore complete communication is required between the science team and flight crew to determine the best course of action in each specific case.

COSPEC determinations of volcanic SO_2 flux can be made by three principle methods: surface stationary, surface mobile and airborne (see Chapter 2). The aircraft method of SO_2 flux determination is generally the most rapid and potentially most accurate. However, the use of aircraft, in and by itself, does not automatically result in well constrained data. It is necessary to perform accurate air navigation and wind vector (velocity) determinations to obtain good flux numbers. In some instances the airborne method is the only way to obtain data, for example, if a plume is above lower clouds or haze, it may be difficult or impossible to obtain data from the

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surface. However, it is also the most expensive method, and if costs are based on flight time then efficient air navigation methods can be used to reduce the amount of flight time and therefore allow funds to be used for other purposes or for more frequent COSPEC measurements.

This chapter is written so that any aircraft can be used to achieve accurate flux determinations equivalent to that obtained by research aircraft and pilots. Those researchers who have access to research aircraft and pilots should already have similar procedures in place to obtain good wind vectors and traverses efficiently. It is not intended that procedures described in this chapter be used in a step-by-step manner but rather as tool to understand the important elements of an aircraft based COSPEC mission. Adapt these procedures to your particular circumstances of volcanic activity, atmospheric conditions, aircraft availability, time, funding, pilot skill, navigation equipment etc.

Air navigation will be discussed in detail only because it is a required element of accurate gas flux measurements from volcanoes. Simply stated precise flying and navigation are as necessary a component to volcano gas flux measurements as thorough clean room procedures and technically competent operation of laboratory equipment, are to geochemical analyses. A competent pilot well versed in the requirements of these measurements can take over most elements of a COSPEC mission, however, scientists need to ensure that the proper data is obtained to reduce the uncertainty in flux measurements to a practical minimum.

It is assumed that the reader has familiarity with COSPEC calculations which can be summarized as follows: the COSPEC views the plume from below and produces an output that is proportional to the overhead burden (column amount) of SO_2, which is calibrated against internal calibration cells of known path-length concentrations. A cross section of the overhead burden is determined by moving the COSPEC along a traverse below the plume (Fig. 1). This cross section of the overhead burden is then multiplied by the plume velocity to determine the flux (see Stoiber et al., 1983; Chapter 2).

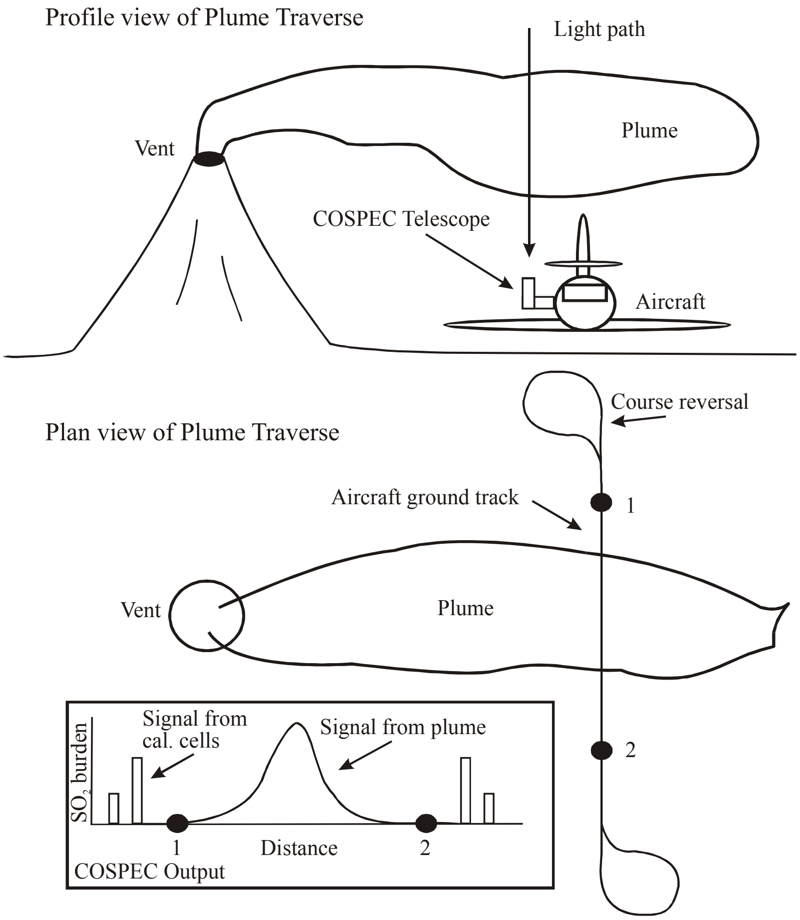


Fig. 1. Typical relationship between volcano, volcanic plume, aircraft traverses and COSPEC output.

Typically, the largest source of error in most COSPEC determinations is uncertainty in the plume velocity. Plume velocity is generally assumed to be equivalent the wind velocity at the altitudes that plume covers (although direct measurements of the plume velocity from the ground can be attempted by tracking distinct portions of the plume, in some cases). Table 1 shows the percentage error introduced into COSPEC determinations under varying wind velocities with uncertainties in wind velocity measurements of plus or minus 0.5*,* 1 and 2 m s^{-1} (1 m s^{-1}= 1.9427 knots).

Table 1. Percent error introduced in SO_2 flux determinations for wind vector uncertainties of 0.5, 1 and 2 m s^{-1} at various wind speeds.

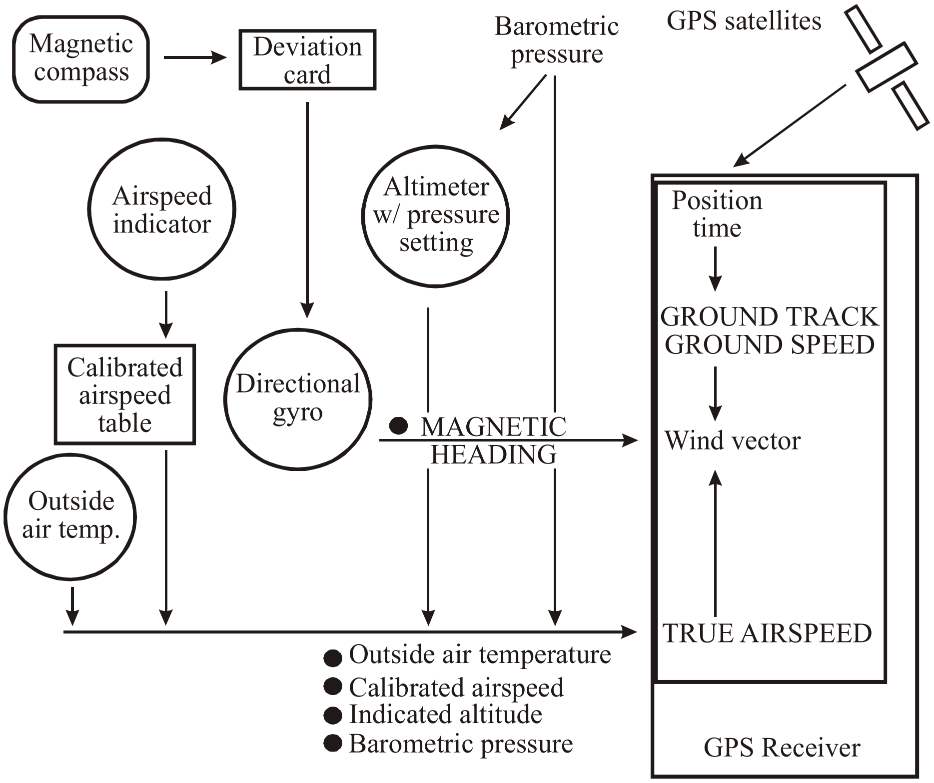
Actual wind velocity (m s^{-1})	1	2	4	10	20
Wind speed uncertainty (m s^{-1})	**Percent error**				
0.5	50	25	12	5	2.5
1	100	50	25	10	5
2	200	100	50	20	10

Wind speed determinations to within 0.5 m s^{-1} are probably the practical limit one can obtain with, standard aircraft instruments and off-the-shelf Global Positioning System (GPS) receivers. A 1 m s^{-1} uncertainty in wind speed determinations can be achieved consistently with proper equipment, precise flying and measurement procedures. A 2 m s^{-1} uncertainty is more typical with lesser navigation equipment, poor piloting technique or difficult conditions such as large amounts of wind shear or turbulence at the plume altitudes. Although, it does nott take much work to achieve results worse than ± 2 m s^{-1}.

Highlighted in Table 1 is the large amount of uncertainty associated with lower wind speeds. In high wind speed conditions, one should be able to get wind speed determinations with a low uncertainty. However, typically during high wind speed conditions at volcanic peaks, there is strong wind shear involving downwind eddies, rotors and down drafts that can put considerable amounts of SO_2 into slow moving areas below the main body of the plume. Therefore, any one measurement may not fully describe the rate of transport of the total overhead SO_2 burden. Multiplying the total overhead burden of SO_2 with the wind speed for the upper portion of the plume will result in an over estimation of the SO_2 flux and use of the wind speed for the lower altitude portion of the plume will result in an underestimation of the flux. One also may not typically rely on a single wind speed determination upwind of the volcano. These situations can only be resolved by careful wind speed determinations at the main plume altitude and below to determine the average plume velocity, combined with careful interpretations of the COSPEC charts to make a reasonable determination of what SO_2 is moving at what speed. Many times the lower portions of the plume will be moving in a slightly different direction from the upper portion of the plume creating a shoulder on one side of the peak on the COSPEC output that plots SO_2 column amount versus distance (time). However, this same shoulder may also be caused by a wind shift. All of these considerations lend credence to the idea that wind vector determinations should be performed carefully, frequently, covering and bracketing the altitudes where SO_2 exists if one wants to achieve optimum results. This can only be done if the COSPEC technician/scientist establish and maintain a close working relationship with the pilot so that the wind field can be well characterized. With modern GPS receivers this requires little additional effort.

2. DATA SOURCES FOR AIR NAVIGATION RELEVANT TO COSPEC DETERMINATIONS

Air navigation utilizes data from the flight instruments combined with position and time data (Fig. 2). The flight instruments provide the following data relevant to navigation: indicated airspeed, magnetic heading, outside air temperature, and indicated altitude. True airspeed (the velocity of the aircraft through the air) can be calculated from the indicated airspeed with the use of a calibrated airspeed table, temperature, indicated altitude and barometric pressure data.



● Indicates data that must be entered manually into portable and low-cost panel mounted GPS receivers to calculate wind vector during a traverse of any heading. Alternatively, one can fly parallel to the wind vector in an upward leg and then a downwind leg reading the ground speed directly from the GPS receiver. One half the difference in ground speed between these two legs is the windspeed.

Fig. 2. Diagram shows the data that is used for determining information used in COSPEC calculations using any light aircraft and a portable or panel mounted GPS receiver. Position and time of fixes at the beginning and end of traverses as well as any other point such as peak SO_2 reading are determined from the GPS satellite constellation. This data is then used by the GPS receiver to determine ground track and ground speed. The ground track should be perpendicular to the plume and the ground speed should be constant during a traverse. The ground speed data can also be used to determine wind speed by flying an upwind and downwind traverse parallel and adjacent to the plume at the plume altitude. One half the difference between these two traverses is the wind speed at that altitude. One can also calculate the wind speed for a traverse of any orientation by entering data from the flight instruments (large circles) into the GPS and then allowing the GPS receiver to use position and time data to calculate the wind vector. This is useful when calculating wind vector when flying to and from the volcano. This technique can be also be used when flying the COSPEC measurement traverses to determine the vertical wind velocity gradient which is useful when determining the correct plume velocity in situations where the plume is vertically spread out.

Barometric pressure is obtained from a surface facility such as an airport or weather station nearest the volcano. In remote areas, one can obtain the barometric pressure before taking off by setting the aircraft's altimeter to the field elevation and noting the pressure indicated in the pressure setting window of the altimeter.

Position over points on the ground, along with time from a stop watch, can be used to determine ground track, ground speed and traverse length. This can be done by starting the timer over a landmark and flying a constant magnetic heading, altitude and airspeed until over another landmark where the time is also noted. However, it is much easier to use electronic navigation equipment to collect position and time data. With the low cost aviation GPS receivers, it has never been easier to obtain good position and time data. Aviation GPS receivers determine time and position from the constellation of GPS satellites and calculate ground track and ground speed from this data (Fig. 2). If one enters the data from the flight instruments listed above, a built-in flight computer in most aviation GPS receivers will calculate the wind vector (velocity). Ground based radio navigation can still be used were it is available (e.g., VORJDME. RNAV, LORAN) as well as inertial navigation systems found in some aircraft. However, some of the ground based navigation systems are being phased out or reduced, and are less accurate than GPS, which makes GPS the best choice for COSPEC missions.

3. GLOBAL POSTIONTING SYSTEM RECEIVERS

With the advent of the Global Position System and inexpensive panel mounted and portable hand-held models available, precise navigation (horizontal location to ± 5 m) is available for any aircraft. The available features and cost is changing so rapidly that any recommendation to purchase a specific make and model would quickly become obsolete information. All makes of GPS receiver collect position and time data from the constellation of GPS satellites. Also these receivers will save any position as a fix as well as have a course deviation indicator to allow a pilot to fly to and from fixes representing, for example, the endpoints of measurement traverses.

There are a number of features that one should look for when purchasing a GPS for airborne COSPEC determinations. First the GPS should be an aviation model with a built in flight computer to do any of the calculations required for data analyses and wind vector determinations. These flight computers can also calculate distances and bearing between any two fixes which is useful for calculating traverse length or angle between the traverse arid the plume. The GPS should have an external antenna that can be placed on the glare shield or on the inside of the windshield to assure continuous reception. Moving map screens are useful for situation awareness and are now available on low cost models. An RS-232/USB port is very useful for downloading data to a computer. Aviation models of GPS receivers will also allow one to convert units making calculations easier. For example, during the flight one can set up the units to be in nautical miles, knots and degrees from magnetic north for easy communication with the pilot and then change to SI units when making the COSPEC SO_2 flux calculations. It is important to realize that at the time of this writing there is no standardization in GPS receivers in terms of their operation, keypad, displays etc. and therefore reading the manual and practicing with the particular instrument that one plans to use for data collection is necessary.

4. PILOT/SCIENTIST COMMUNICATION

4.1. Terminology

A possible source of confusion between pilots and volcanologists is the term for the local difference between magnetic north and true north. Volcanologists call this difference declination and pilots call it variation but they refer to the same thing. For an easterly variation (declination) magnetic north is east of true north. Deviation is an aviation term for error in the magnetic compass due to the interference of the aircraft structure and electronics.

4.2. Magnetic and true north

All headings flown in aviation are degrees from magnetic north (1-360 degrees) since this is what the flight instruments display. However, the course flown over the ground is typically reported in true because this is what one would draw on a chart since charts and maps have grid lines based on true north. All winds in aviation are reported in true (e.g., winds aloft forecast) except at airports where they are reported in magnetic. The GPS receiver can be set up to work in either true or magnetic, can be switched back and forth, and may display both simultaneously. It is useful to be able to move back and forth between the two systems to rapidly deal with the different data. The simple rule is "West is best, east is least" - which is a pneumonic device for the following formula:

$$\text{Magnetic Heading} = \text{True Heading} - \text{Easterly Variation (Declination)} \quad \text{OR} \quad + \text{Westerly Variation (Declination)} \tag{1}$$

A quick look at a GPS unit that displays both headings will clear up any confusion that may arise in flight. When performing wind calculations or determining the orientation of the plume and the heading required for a perpendicular course to the plume, one should be consistent and work only in true or magnetic to prevent any errors.

4.2.1. Magnetic North System

Generally it is easiest to work in magnetic if you are using data from the directional gyro (which displays magnetic heading) or working closely with the pilot so that you are giving him/her headings to fly. If your GPS is set up to display magnetic and you have calculated the wind direction in magnetic (or plume orientation in magnetic) you can readily communicate to the pilot what heading to fly (with appropriate wind correction angle) to be on a perpendicular traverse to the plume. The only time one has to convert to true is when plotting data on the map (chart).

True North System

Alternatively one can set up a GPS receiver to display true headings. Then after determining plume orientation, tell the pilot what true course to fly and have them make the necessary calculation to determine appropriate heading. This can be easily performed by the pilot, by adjusting heading while viewing the ground track information on the GPS receiver, until the proper ground track is achieved. Working in the true system is also easy when the pilot is flying from one fix to another since he/she will simply use a course deviation indicator on their GPS receiver to determine what heading to fly and you can collect and plot data in true.

Crew size

The best crew size for COSPEC operation is generally three. A pilot to fly the plane and to be concerned primarily about safety (e.g., situation awareness with respect to terrain, etc.), precise heading, altitude and airspeed control and GPS operation. A second person to operate the COSPEC and data recording/display devices and a third person to navigate. This third person should ideally operate a portable GPS that will store data for COSPEC calculations and make wind vector calculations. This third person can also plot plume orientations and traverses on the chart; maintain situation awareness with respect to aircraft heading and plume orientation; and determine or assist the pilot in selecting headings to fly. Close coordination between the navigator and pilot is required. In some situations it may be best for the pilot to also perform the duties of the navigator such as in a two person crew or if no one is competent with GPS or required procedures/calculations.

Ideally the COSPEC operator and pilot can see the map (chart) where the navigator has plotted plume orientation, traverses and fixes on, and the navigator can see the COSPEC data output display device. There has to be close communication between these two operators if there is not a direct data link that will co-register the GPS time and position data with the COSPEC data output since every fix identification number that is collected by the navigator and/or pilot will have to be manually marked on the COSPEC output. Other crew sizes will also work, from a one person pilot/COSPEC operator up to the limitations of the aircraft. Communication between all participants is an important element to a successful mission.

4.3. Additional considerations

- It is useful to have a couple of copies of appropriate aviation charts in the aircraft during the flight. If everyone is using the same chart for navigation, piloting and data plotting the risk of miscommunication is reduced.
- Certain radio or other electronic equipment may interfere with COSPEC signal. If interference is noted try to determine which equipment is the cause and keep its use to a minimum especially during data collection.
- Direct sun into the telescope can damage the COSPEC. Use the telescope extension on the end of the right angle bend to limit the angles in which direct sun can enter the instrument. All participants, especially the pilot, should stay cognizant of the sun orientation to limit the opportunity of direct sun entering the instrument during any maneuvering.
- An intercom system with noise attenuating headsets makes communications easy and should be used whenever possible. In situations where they are not available, develop a system of simple hand signals and one or two word statements to communicate.
- Make sure the COSPEC/computers/dataloggers are properly strapped in so as not to bounce around or fall out of the aircraft.
- Make sure the crew is properly strapped in an approved manner with approved equipment so as not to get bounced around during turbulence or ejected out the opening (if it is large enough) where the COSPEC is projected.
- Corrugated plastic board or cardboard reinforced with duct tape can be used to cover the opening where the COSPEC telescope is sticking out to reduce wind noise (see Chapter 2). Be sure no material can break loose from the aircraft of get blown out of the aircraft.
- All modifications must be approved by a qualified inspector/mechanic and the pilot flying the aircraft.

5. ESTABLISHING FIXES AND WAYPOINTS

With the push of a button any GPS can save a “fix” at any time. This fix will be defined by latitude, longitude, time and altitude. This fix is only useful if it is also co-registered on the COSPEC data output either automatically through a computer interface, or manually on a chart recorder tape or computer storage device. One can select a fix at the beginning of a traverse and at the end. Fixes can also be created along the traverse at the first measurement of SO_2, peak SO_2 level, etc. Location of fixes of important features (such as vent location) can be entered manually, by obtaining the latitude and longitude from a map, and used for navigation reference. Fixes at the end of traverses can be also used as way point (a point to fly to or from). Two of these way points can be used to define a traverse so that one flies back and forth between the same points multiple times.

For the purposes of this chapter, when the term fix is used, it is assumed that the operators make a fix with the GPS (by pushing the fix button) and record the fix number on the COSPEC data output either manually or through a computer interface. Those operators with continuous co-registration of COSPEC and GPS are continuously taking fixes and therefore can select which ones to use after a traverse is completed. However, operators who do not have continuous co-registration of GPS position data and COSPEC output can also determine the position and time of any point on a COSPEC output as long as it in between two fixes and the pilot has maintained a constant airspeed and heading between the fixes.

Also for the purposes of this chapter, when the term traverse is used, it is assumed that it is defined by endpoints (fixes or way points) and the pilot will fly a constant airspeed, altitude and heading or ground track between them. We will also assume that the calibration cells will be inserted at the beginning and end of the traverse either just outside of the fixes or inside, but only once the aircraft is established on the traverse heading and before the plume is encountered.

6. SETTING UP TRAVERSES

There are two principle ways of flying traverses which may be called the fixed-point method and fixed-heading method. In the fixed-point method, one establishes two fixes that define the ends of the traverse. Then one flies back and forth between these fixes. In the fixed heading method, one determines the headings that will maintain a perpendicular course to the plume and allow the aircraft to remain the same distance downwind of the volcano. Then one simply uses these headings to fly the traverses. New fixes are created at the beginning and the end of each traverse. These two methods are very similar, and if the fixed-point method is flown accurately in a steady wind condition, a constant heading can be kept and is therefore essentially the same as the fixed-heading method except it takes more time to set up and fly. Likewise if a correct wind correction angle is used in the fixed heading method, the aircraft will fly essentially along the same path on each traverse and is therefore very similar to the fixed-point method. Both of these methods will be described in the following sections.

The common element to each of these methods is to first determine the location and orientation of the plume. The surest way to find the orientation of the plume is to fly under it on a traverse with the COSPEC running and then select a fix at the peak SO_2 signal. The bearing from the peak SO_2 signal to the vent is the orientation of the plume. On this first traverse, one is simply flying a heading that one assumes will produce a perpendicular course to the plume and is therefore using the fixed-heading method.

6.1. Fixed-heading method

The fixed-heading method allows one to collect data more rapidly, requires no set up, and is therefore best used when time (and money) are limited, the plume location is shifting or of such large scale that only one traverse can be completed per mission (Fig. 3). This method also works best if there is only one GPS unit and the member of the science team who is navigating wants to retain control of the GPS to be sure proper fixes are saved and data (e.g., wind vectors) are collected and is competent at giving the pilot correct headings to fly (or has set up a procedure with the pilot so they can work together to determine what headings to fly).

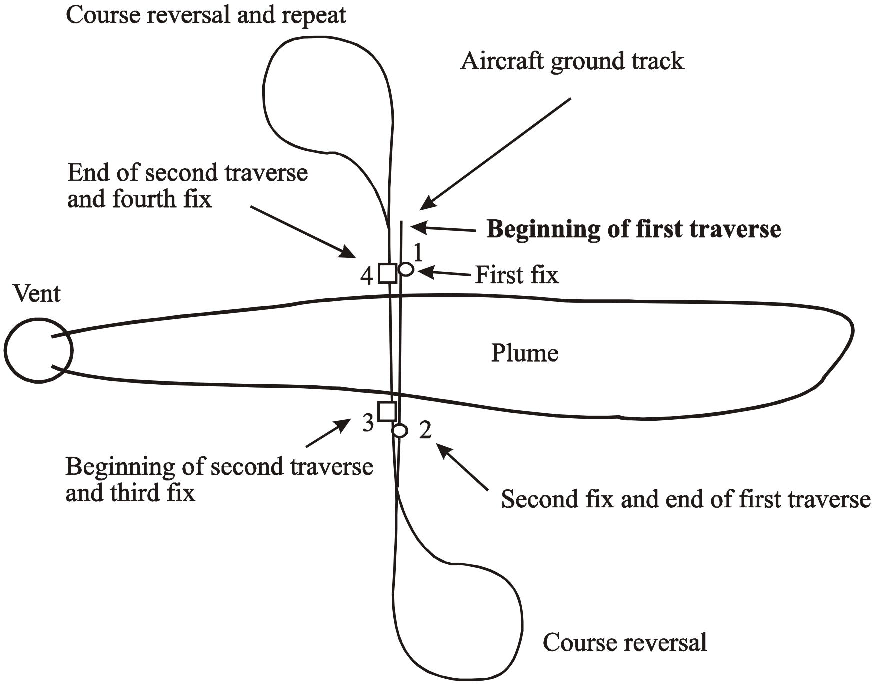


Fig. 3. Fixed-heading method.

Before flying to the volcano, look at forecast winds, pilot reports and direct observation of the volcano (if possible) to asses the orientation of the plume. Next, while flying towards the volcano, level off at the altitude of the plume, if it is visible, and fly a constant heading towards the volcano while performing wind vector determinations (as described below in *section 7*). The wind vector can then be plotted from the crater to see the likely position of the plume.

Next, descend below the plume, as it is approached, assuming there is sufficient altitude to do so, level off and fly a traverse perpendicular to the wind vector downwind of the volcano. This first traverse should always be a fixed-heading method since one will not be sure of the actual orientation and width of the plume until one flys under it so it would be unreasonable to have a fix on the far side of the plume for the first traverse. If we fly a heading that will give us a perpendicular course to the plume, we can make the fix on the far side of the traverse when we exit the plume. Once the plume orientation is known, one simply flies a heading the will be perpendicular to the plume. Table 2 and Equation (2) can be used to determine how much of a wind correction (crab) angle should be flown to maintain a path perpendicular to the plume (Fig. 4).

Table 2. Approximate wind correction angle used to add or subtract from desired magnetic course to obtain magnetic heading to be flown to achieve a traverse perpendicular to the plume orientation. For example, an aircraft flying at 100 kts perpendicular to a 30 kts wind (and plume) from 180° magnetic should fly a headings of 252° magnetic and 108° magnetic to maintain an approximately perpendicular orientation (270° magnetic and 90° magnetic) to the plume and to remain the same distance downwind of the volcano on successive traverses.

Wind velocity as % of Aircraft True Airspeed (TAS)	Approximate wind correction angle required to fly a traverse at 90 degrees to the wind
5	3
10	6
20	12
30	18
40	24
50	30

(2) Aircraft Heading = Desired aircraft ground course ± Wind correction angle

(Aircraft heading and desired aircraft ground course must be both with reference to magnetic OR true north. Since Aircraft Headings are always given with reference to magnetic north it is best to convert desired course from true to magnetic before the calculation. Desired course for a COSPEC traverse is 90° from the plume orientation)

Alternatively one can simply make a best guess for heading and then make small adjustments until the ground track (displayed on GPS) is perpendicular to the plume orientation. Fixes are made at the beginning of the traverse (after heading, airspeed and altitude are established and stabilized), at the peak SO_2 value and at the end of the traverse. Once out from below the plume, make a fix, calibrate and then turn around (e.g., 80°-260° turn) and fly the new heading that will produce a perpendicular course to the plume and enter a fix before entering the area below the plume (if the pilot maintains a constant heading and airspeed, the fix does not have to be at the beginning of the SO_2 signal since the chart output can be calibrated for distance). If proper wind correction angles are used on the traverses, one can maintain the traverse at approximately the same location downwind of the volcano. The temporal variation of the SO_2 flux can still be resolved even if the traverses are not at the same location downwind with the use of the wind speed data. However, if one decides to move further downwind or upwind this is easily accomplished. Since a constant heading is maintained throughout the traverse, the wind vector determination can be made continuously. A combination of fixed heading and fixed point methods can be used on any one mission to suit conditions or objectives.

It is useful to fly this first traverse relatively close into the volcano, safety permitting, so that the orientation of the plume can be confirmed quickly (one can also use this quick traverse to make sure the COSPEC and data recording device are set up correctly). During this traverse, make a fix at the peak SO_2 signal. The vector defined by the location of the peak SO_2 signal to the vent is the actual orientation of the plume, so use this for determining all future traverse headings and also to check on any wind vector determination.

This plume-peak SO_2 bearing can easily be determined by one of two ways using aviation GPS receivers. First, by manually entering the latitude and longitude of the vent as a fix or way point (preferably before the flight), then a fix is made at the peak in the COSPEC signal (by pushing the fix button on the GPS when directly under the peak SO_2 signal). One can then use the aviation computer in the GPS to calculate the bearing from the peak to the vent. This bearing is the orientation of the plume. In the second method, one can plot the latitude and longitude of the fix under the peak SO_2 signal on a map (chart) then a line drawn from this point to the vent defines the orientation of the plume. All traverses should be approximately perpendicular to this orientation if possible (remember a trigonometric correction can be applied to any traverse that is not perpendicular, but at known angle, to the plume). The orientation of the plume (wind) is also required when determining wind speed by flying parallel, upwind and downwind, the wind vector as described in the Wind Vector Determination section. Now move to the desired position downwind to perform the remaining traverses. One should be far enough downwind so that you

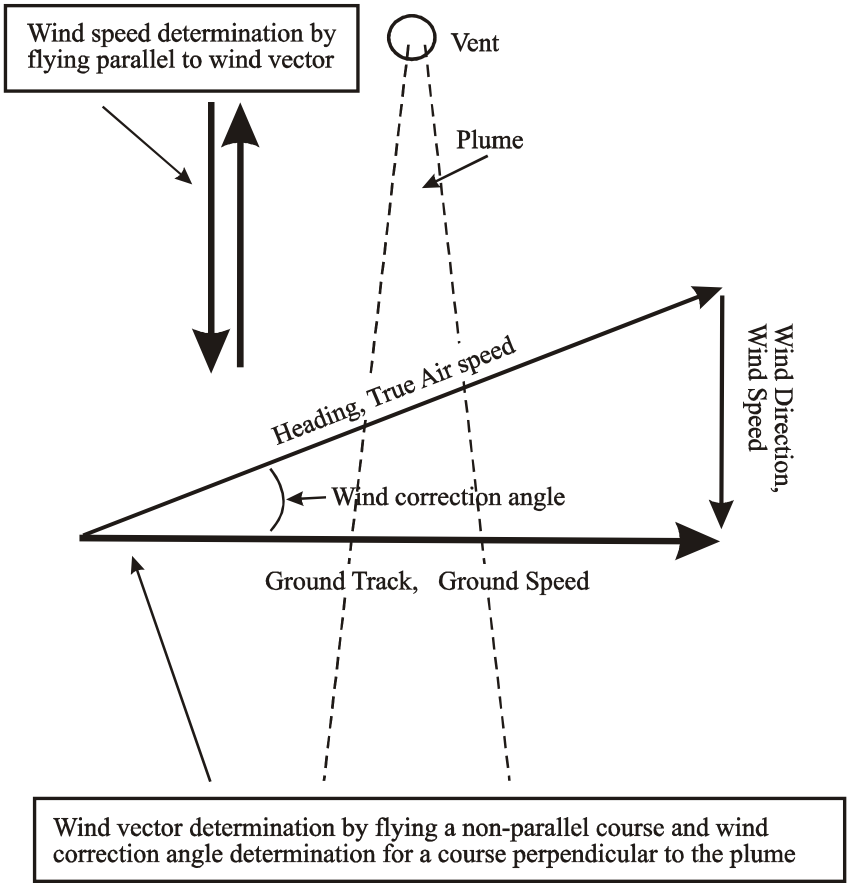


Fig. 4. Wind triangle diagram showing the three vectors. The ground vector is defined by the ground track and ground speed of the aircraft. The air vector is defined by the heading of the aircraft (the orientation of the aircraft) and it's true airspeed. The wind vector is defined by the wind speed and the direction the wind is coming from. The wind vector can be solved if the ground and air vectors are known by vector arithmetic, trigonometrically, graphically or simply by using the flight computer built into the GPS receiver. The angle between what the aircraft is attempting to fly (the air vector) and what actually is flown in reference to the ground (the ground vector), is called the wind correction angle or crab angle. For the wind vector to be solved, all of the direction data has to be consistent (either reported in degrees from magnetic or true north). See the text for a discussion of which system may work best for you. Also shown are the parallel flight paths for wind speed determinations.

are under the plume for a few minutes to obtain good resolution.

One can now continue using the fixed heading method, creating new fixes on each traverse, and useing a set of fixes as points to fly to and from for all the remaining traverses with the fixed-point method described below.

6.1.1. Advantages and disadvantages of the Fixed-Heading method

Advantages

- Appropriate method for the first traverse
- Quicker
- Easier to make wind determination on each traverse
- Easier to adapt to changing conditions
- Easier to explore variations in SO_2 at varying distances downwind
- Appropriate method for very large scale plumes

Disadvantages

- Location of the traverse may not be the same for each traverse
- One ends up with two additional fixes for each traverse which increases the amount of data that has to be stored and utilized
- Length of traverses may be different which may make data reduction more time consuming
- If there is only one GPS and a member of the science team needs to use it, then they have to be competent in its use to give the pilot headings to fly that will give a perpendicular course to the plume and allow the traverses to occur at the same location downwind if that is what is desired

6.2. Fixed-point method

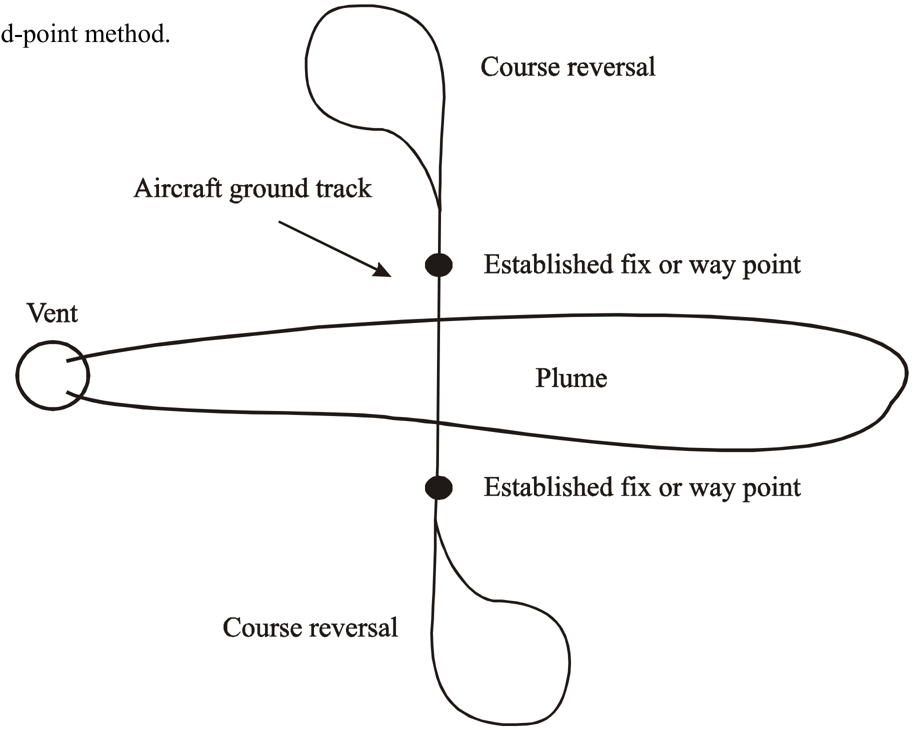
The fixes that were made during the first traverse can be used as way points if this first traverse is located at the appropriate distance downwind. If it is not at the appropriate distance downwind, move to the desired location and start another fixed-heading traverse, making fixes at the beginning and end that will be saved as way points to fly to and from on all subsequent traverses (Fig. 5). Typically, one should have the way point located so that a few minutes of flying time occurs before the first SO_2 signal so that it can be used throughout the mission even if the plume shifts. Now the pilot simply flies between these two points, using the course deviation indicator on the GPS to navigate, while the COPSEC measurements are made. If the pilot maintains a constant ground track and airspeed, then the chart recorder can be calibrated for distance to simplify flux calculations and make less critical the relative location of the fixes and plume.

The calibration of the COSPEC can be made inside or outside the way-points but necessarily outside of the plume. The pilot may make small course corrections to stay on course between the two way points (i.e., he/she will be trying to make sure the ground track of the aircraft matches the direct course between the way points by flying a heading that incorporates a wind correction angle). While heading adjustments are being made, wind vector determination cannot be made with the typical hand-held GPS units used in light aircraft since a constant heading must be maintained. However, if a constant heading is held for a period of time, this determination can be made and is useful to characterize the wind field around the plume, especially if the plume displays a significant vertical distribution.

There is an important distinction between the fixed-point method and the fixed-heading method. When the pilot is flying between two fixed points he/she must use the GPS to observe the course deviation indicator. If there is only one GPS, the pilot will also have to make any fixes that may be required such as at peak SO_2 location and most importantly let the COSPEC operator know when the fixes signaling the end of the traverses are reached so he can mark the COSPEC output. Also, if wind speed vector determinations are desired along the traverse, then the pilot will also have to perform them, which on some portable GPS models can be difficult while trying to track a ground course. If two GPS receivers are available (e.g., one mounted on the panel and one portable, or two portable) then the pilot and navigator can set the same fixes up in their respective GPSs, then while the pilot navigates between the two using the course deviation indicator, the navigator can collect additional fixes at the first measurement of gas, smell of gas, peak SO_2, etc. These can then be plotted on a chart by the navigator and on the COSPEC output by the COSPEC operator. In addition, the navigator can also collect wind vector data along the entire traverse to help assess the wind field around the plume. This dramatically reduces the workload of the pilot and allows for a greater quantity of data to be collected. Alternatively, the navigator can use the one GPS receiver if he/she can give the pilot (or work with the pilot to determine) headings to fly when using the fixed-heading method described in the following section.

Advantages and Disadvantages of the Fixed-point method

Fig. 5. Fixed-point method.



Advantages:

- All traverses are flown at the same distance downwind so any variations observed are related to the temporal variation of the SO_2 emitted from the volcano if the wind is well characterized

- Data reduction may be quicker since every traverse is the same length

Disadvantages:

- More time is required for each traverse due to the necessity of flying to the way point (fix) once out from under the plume
- If plume location shifts significantly one may have to set up new way points
- More difficult to obtain wind data during the traverses due to the likelyhood of minor course corrections to maintain a ground track that links the fixes that mark the endpoints of the traverse
- If only one GPS receiver then the pilot must use it for the course deviation indicator display and he/she will therefore have a higher workload because of additional requirements of entering additional fixes, performing wind vector determinations (if desired), and signaling the COSPEC operator when fixes are reached

7. WIND VECTOR DETERMINATIONS

One can determine a wind vector by simple vector arithmetic utilizing the vector of the aircraft thought the air (described by magnetic heading, which is the orientation of the aircraft in degrees from magnetic north and true airspeed, which is the speed of the aircraft relative to the air; we will call this the air vector) and the vector of the aircraft over the ground (described by ground track which is the actual flight path of the aircraft over the earth's surface and ground speed which is the actual speed of the aircraft over the earth's surface; we will call this the ground vector) (Fig. 4). The magnetic heading and true airspeed of the aircraft is what one is attempting to fly and will be equivalent to the ground track and ground speed in a no-wind condition. However, if there is a wind, this will cause the aircraft to fly a ground track and ground speed that is different than the magnetic heading and true airspeed of the aircraft. The analogy of a canoe in a river works well to visualize this. The calculation can be performed by most aviation GPS units or manual flight computers, by plotting the vectors on graph paper and trigonometrically or by vector arithmetic. The quickest method is to use an aviation GPS receiver where the ground track and ground speed are automatically determined and you simply enter the magnetic heading and calibrated airspeed, temperature, altitude, and barometric pressure and the builtin aviation computer in the GPS will calculate true airspeed, then the wind vector (Fig. 2). In more advanced aircraft, all the data from the flight instruments will also be fed into the flight computer and one only need look at a display where the wind speed will be indicated. The aircraft has to be maintained at a constant indicated airspeed, altitude and heading for this to work on the portable and panel mounted GPS systems where flight instrument data is entered by hand.

One should, whenever possible, determine the direction of the plume by making a fix at the location of the peak SO_2 signal along the traverse so that a line from the vent to this fix is the plume orientation which should be parallel the wind vector (the wind vector is described as an azimuth, in magnetic degrees from north, of where the wind is coming FROM, e.g., a south wind is 180, a west wind is 270, a SE wind is 135, etc., and speed). The plume orientation can then be used to check the wind speed vector determinations performed while flying a traverse. If the direction determined from the wind vector determination does not match this direction, than the calculation is off and the velocity can be assumed to be wrong, or alternatively you are not at the altitude of the main body of the plume. Also, the wind direction is used to calculate the velocity of the wind by flying parallel to the wind (described below).

7.1. Wind determination while flying a traverse

Wind vectors can be determined while flying a traverse if one holds a constant heading, airspeed and altitude. These determinations can be made at the plume altitude while flying toward the plume from the airport or they can be made on each traverse under the plume while making the COSPEC measurements if the traverses are of sufficient length to provide enough time. When making a determination under the plume, the wind speed and direction may be different from the actual plume altitude, however, these measurements are still useful to characterize the wind field around the volcano, especially if the plume is dispersed over a large range of altitudes due to wind shear.

The simplest way to make a wind vector determination with this method is to use an aviation GPS unit. As one begins a traverse and the aircraft is stabilized in level flight, the following data are entered into the GPS unit: magnetic heading, calibrated airspeed, outside air temperature, altitude and barometric pressure.

The magnetic heading can be obtained from the magnetic compass situated on the glare shield above the instrument panel or mounted on the wind screen. The aircraft has to be stabilized, level, non-accelerating flight without turbulence to read this compass. The magnetic heading can also be read from the directional gyro located at the bottom center of the panel. This instrument can be read at all times, however, it must be set to the magnetic compass, either manually every 15 minutes or automatically through a slave system. Work with the pilot to make sure you or they are entering the correct magnetic heading into the GPS unit.

The calibrated airspeed is determined by reading the indicated airspeed on the airspeed indicator located at the top left of the panel. This indicated airspeed is then looked up on a calibrated airspeed table in the Pilot Operating Handbook to determine the calibrated airspeed. For practical purposes the calibrated airspeed and indicated airspeed are very similar (generally within 1-2 knots) for the airspeeds typically used during COSPEC determinations in general aviation light aircraft. However, the pilot should look at the handbook for that particular aircraft to be sure. If this is the case, then one can just use the airspeed directly from the airspeed indicator. However, there are a number of problems that can be introduced when making COSPEC measurements. The airspeed is determined by measuring the difference in static pressure and ram pressure. The static pressure port is typically located behind the cabin on most light aircraft and therefore open windows, doors and protruding COSPEC telescopes can create turbulence directly over these ports that may create errors in the indicated airspeed. This can be avoided by making sure the telescope does not protrude in front of the static port and using the calibrated airspeed tables for open doors and windows in the Pilot Operating Handbook for the particular aircraft. Calibration of the airspeed indicator can be checked in flight during a no wind condition.

The outside air temperature is obtained from the temperature probe and read inside the aircraft. Ask the pilot for its location. The altitude is read directly from the altimeter that has been set with the local altimeter setting (local barometric pressure) and this local barometric pressure is also entered into the GPS. The local barometric pressure is obtained from the nearest airport or from the altimeter by setting it to field elevation when on the ground and reading the barometric pressure.

The altitude, outside air temperature, calibrated airspeed and barometric pressure will probably not have to be changed during a series of traverses. Therefore, only the heading will have to be changed on successive traverses.

Advantages and Disadvantages of wind vector determinations on a traverse

Advantages

- Measurements can be made while making COSPEC determinations.
- Measurements can be made while flying to the volcano from the airport.
- During a COSPEC measurement traverse, the wind vector determinations are below the plume and compliment measurements made at the altitude(s) of the main body of the plume by showing the rate of shear over the plume altitudes and help in assessing average plume velocity

Disadvantages

- Measurements made during the COSPEC traverses are at an altitude below the level of the plume and therefore may not represent the velocity of the main body of the plume
- Requires calibrated airspeeds (airspeed indicator needs to be calibrated) and calibrated airspeed table
- Requires data entry of heading, calibrated airspeed, temperature, altitude, barometric pressure setting into the GPS receiver
- Requires flying a fixed-heading and is therefore not very compatible with the fixed-point method of traverse when course changes may be required to keep on the ground track defined by the two fixed points

7.2. Wind speed determinations flying parallel the wind vector

This is probably the easiest way to make a wind speed determination. Once the plume direction is known (defined by a line from the vent to the location of the peak SO_2 signal in the COSPEC traverse) the aircraft is flown up to an altitude of the main body of the plume. The aircraft is then flown adjacent to the plume on a heading that is parallel to the plume orientation. The aircraft is allowed to stabilize in airspeed and then a fix is taken with the GPS. After several minutes, another fix is taken and the aircraft is then turned around on a reciprocal heading (180 degrees from the original heading) and again once the aircraft is stabilized at the same indicated airspeed as the first leg. A fix is then taken, followed by another, several minutes later. With these fixes, which record location and time, one can calculate the ground speed along each leg. One half the difference in the ground speed between these two legs is the wind speed. Alternatively, one can simply read the ground speed for each leg directly from the GPS receiver display. One can use this feature if the reading is stable during each of the legs or the data is integrated over a period of time. Using this method and a ground speed display is the simplest way to determine wind speed.

Advantages and disadvantages of wind speed determinations flying parallel wind vector

Advantages

- measurements do not require calibrated airspeeds (airspeed indicator can be poorly calibrated)

- simple

Disadvantages

- can not make wind speed determinations simultaneously with a COSPEC traverse or on any course that is not parallel with wind vector.

8. EXAMPLES

8.1. Popocatépetl Volcano, Mexico, 1996

During passive degassing of Popocatépetl in 1997, a NASA sponsored mission to validate TOMS measurements with the COSPECs operated by group of international experts, allowed for airborne determination of the SO_2 flux. Figure 6a shows an example for a portion of one of these COSPEC flights on May 9, 1997. On the flight out to the volcano, wind vector determinations were made to determine the likely orientation of the plume which confirmed the forecast winds. The traverses were begun underneath the plume using the fixed-heading method and then after the traverses were completed, the aircraft was flown up to plume altitude and flown parallel to determine wind velocity.

8.2. Rabaul Caldera, Papua New Guinea, 1994

During vulcanian eruptions from Tavurvur volcano at the Rabaul caldera in 1994, an NSF-sponsored mission from Arizona State led by Stanley N. Williams collected airborne SO_2 flux data (Roggensack et al., 1996). Complex and strong, horizontal and vertical wind shear and large SO_2 fluxes required some modifications to methods for data retrieval. The plume was of such a large scale that the fixed heading method was used since only one or two traverses were completed on some missions. Figure 6b shows an idealized example from a COSPEC flight. Wind speeds at a number of altitudes bracketing the plume altitudes were obtained on the flight to the volcano from New Ireland. Next, a traverse was initiated to pass under what was determined to be the main body of the plume. The plume was very broad and covered an angle of 90 degrees and high concentrations of ash required traverses far downwind. A perpendicular course was set for the main body of the plume that was oriented by the higher altitude winds. After this part of the plume was transected from below, a turn was made to cover the lower altitude part of the plume that was heading more to the north and west. A fix was made at this turn, and along both legs of the traverse winds were determined. The smell of SO_2 in the cabin indicated that some SO_2 was below the COSPEC during this part of the traverse. Since the aircraft was 500 feet above the ocean (considered the minimum limit under these very low visibility conditions), this amount was assumed to be small and not considered in the calculation. However, the wind vector determinations during the traverse were used as representative of this lower portion of the plume. Following the traverse, the aircraft climbed to plume altitude for a series of wind vector determinations. The flux was determined for the two portions of the plume separately using the appropriate wind speed. The total flux from the volcano was the some of these two calculations.

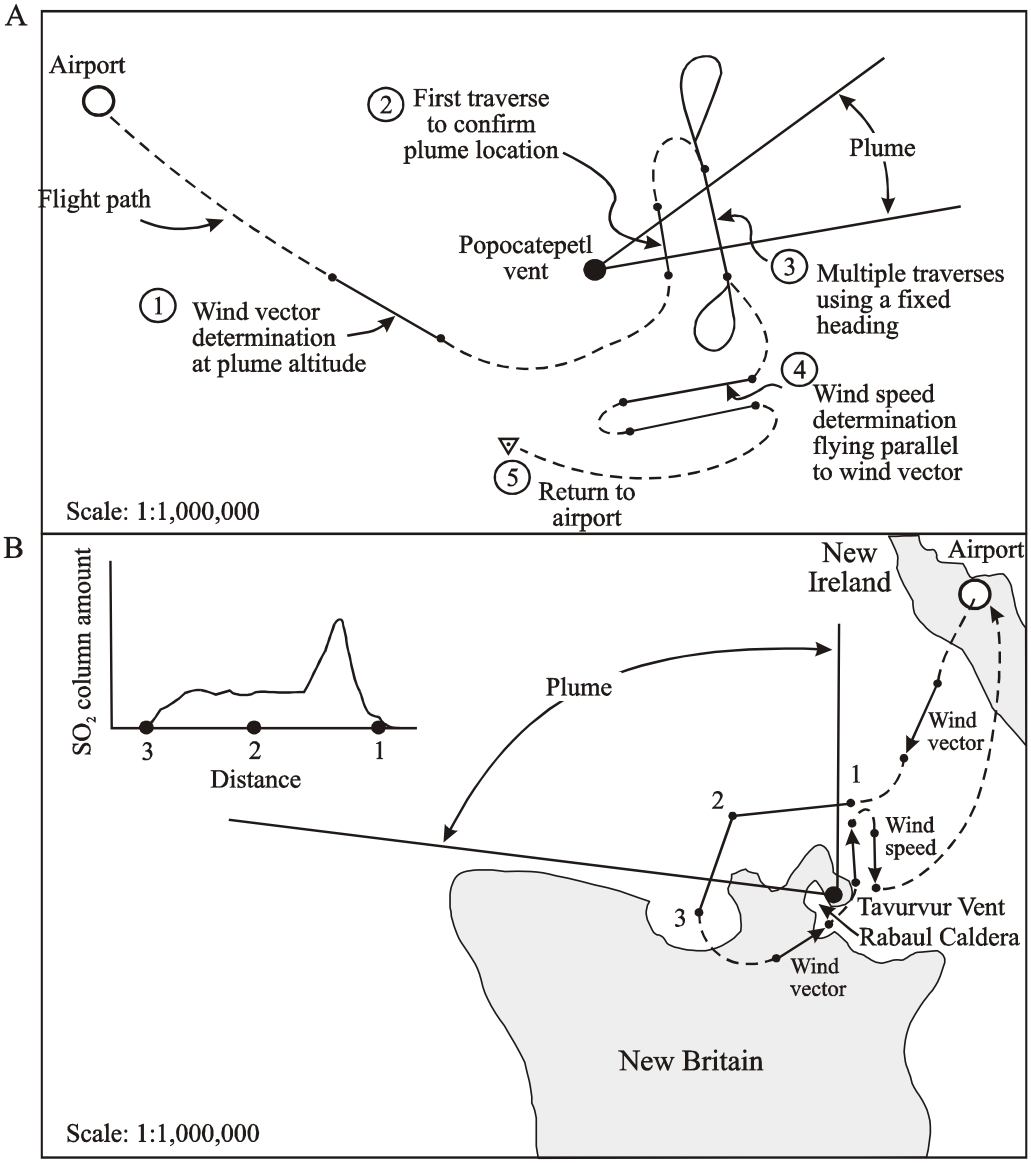


Fig. 6. Example from (a) Popocatépetl volcano, Mexico, 1996 and (b) Tavurvur, Papua New Guinea, 1994.

9. SCENARIO FOR COST EFFECTIVE AND ACURATE COSPEC MISSION

A cost effective method is to combine a number of the techniques described above in the following order:

1) Fly to the volcano at plume altitude and determine wind vector
2) Plot vector on the chart
3) Descend below the plume and set up on a fixed-heading traverse (fly a constant heading that will produce a perpendicular ground track to plume, constant airspeed and constant altitude)
4) Calibrate the COSPEC

5) Make a fix before or when the SO_2 signal begins
6) Determine the wind vector while on the traverse, time permitting
7) Make a fix at the peak SO_2 signal
8) Plot the vent to peak SO_2 signal orientation and use it to check wind speed determinations
9) Make a fix at the exit from beneath the plume (when SO_2 signal ends)
10) Calibrate the COSPEC
11) Make an 80-260º turn if at appropriate distance downwind. Move upwind or downwind if necessary
12) Establish a heading that is perpendicular to the plume
13) Calibrate once established on the traverse heading and before SO_2 signal begins – go to step 5 unless the desired number of traverses have been completed, then go to step 14.
14) After the traverses are completed, climb to plume altitude and fly parallel to the plume orientation. Fly this orientation upwind and downwind to determine wind speed
15) Fly home at plume altitude and again determine wind vectors

10. CONCLUSIONS

Volcanic plumes can present an infinite number of challenges to obtaining good SO_2 flux measurements. Aircraft can be used in the majority of these cases and allow for very accurate wind vector determinations. Accurate navigation is crucial to well constrained SO_2 flux determinations from volcanoes. Close coordination between the flight crew and science team is required for the best results. One should not allow preoccupation with navigation to interfere with obtaining good overhead SO_2 burden (column amount) data with the COSPEC. Bring another person along to handle navigation issues or hand it off to the pilot after you have explained thoroughly what you need during a pre-flight brief.

To make things easier, one can set up simultaneous datalogging of the GPS data and the COSPEC data. More advanced systems also include co-registration of flight instrument data so that all necessary data is simultaneously and continuously collected and the flux calculations are automatic. Such systems can make possible single pilot COSPEC operations or unmanned aerial vehicles to perform volcanic gas flux measurements. Small scale trajectory models could be incorporated into an analysis routine such that all wind vector data are used to determine a complete picture of plume velocity.

Work with your pilot as he/she may have a few efficiency improvements (tricks) for getting the necessary data, especially after he/she becomes familiar with what you are trying to do. One should remember to improvise if any equipment fails or is unavailable. Unlike laboratory geochemistry, the measurements that one makes of gas flux from a volcano are part of an ongoing experiment that can not be shut down and repeated because the conditions/equipment are not perfect. The minimum requirements to acquire constrained SO_2 flux data are an operating COSPEC and a pilot who can fly a straight line. Just make sure one records all necessary data to determine traverse lengths, orientations and wind vectors.

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APPENDIX

CONVERSION FACTORS

Distance

1 nautical mile	1.8531 kilometers
1 statute mile	1.6093 kilometers

Velocity

1 knot	0.51475 meters per second

Magnetic Heading = True Heading - Easterly Variation (Declination)

Magnetic Heading = True Heading + Westerly Variation (Declination)

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