1. Introduction

The purpose of this practical session is to consider the factors that go into designing a satellite mission. For this, you are asked to, as a group, choose a scientific question relating to the composition of the atmosphere that you'd like to answer. For this you'll need to determine which species (one or more) you'd like to monitor, and what time and spatial scales are relevant to the problem at hand. Don't worry too much about the "real-world" feasibility of the mission: it's a thought experiment, not an actual proposal. This document will guide you through some of the choices that need to be made. After an hour each group should present their planned mission, along with a few calculated quantities, including estimated cost.

2. Species and Focus

Most of the information presented today has related to CO_2 and CH_4, both of which are relevant to climate and the carbon cycle. These are also the gases which I know the most about. However if you've got a good idea about ozone monitoring, don't let me hold you back! What you need to decide is which gas or gases you'd like to monitor, and why.

The next step is to consider the area of interest in order to answer your scientific question. For instance, if you'd like to constrain the global CO_2 budget, it makes sense to choose a sensor that can measure CO_2 and an orbit that covers the whole globe. If, however, you'd like to constrain methane fluxes in the tropics, it might be better to choose an orbit with a lower angle of inclination, and perhaps a sensor with a smaller footprint in order to better see between the very frequent cumulus clouds found at tropical latitudes. If you'd rather use the satellite to measure the signal from a restricted geographic "hot spot", perhaps a geostationary or geosynchronous orbit is a better choice.

3. Orbit

Keeping in mind what you've already heard today about orbits, it's time to choose one for your satellite. Sun-synchronous polar orbits are the most commonly used for global earth observation (with good reason), but your scientific question may require a different approach. Regardless, estimate the following parameters for your chosen orbit:

- period
- repeat time
- height
- approximate angle of inclination
- distance between measurements at equator based on repeat time and period
- decay
- footprint (can be determined once you know your sensor)

The full calculations of orbit mechanics are beyond the scope of this session, so some estimations will have to be made. The choice of height, repeat time, and angle of inclination are essentially arbitrary, although they influence the other parameters. The importance of the repeat cycle is shown by the distance between measurements at the equator, the importance of height is shown with the footprint and decay, and the angle of inclination determines how much of the earth is observed in nadir mode. In general, an angle of inclination greater than 90° provides global coverage, and smaller angles reduce the latitudinal extent of the measurements. Most sun-synchronous orbits have heights between 400 km and 1000 km. The choice of repeat time changes the spatial coverage - longer repeat cycles have measurements closer together in space, shorter repeat cycles have measurements closer together in time. The following equations may be useful (making the assumption that all orbits are circular):

$$mv^2/R = Gm_E m/R^2 \tag{1}$$

i.e. to remain in orbit centripital acceleration must be balanced by gravitational acceleration. Here m_E is the mass of the earth (5.9742 $\times$ 10^{24} kg), R is the orbit radius, G is the universal gravitational constant (6.673 $\times$ 10^{-11} Nm^{-2} kg^{-2}), v is the tangential velocity, and m is the mass of the satellite. The radius of the earth is approximately 6378 km.

The period of the satellite is given by:

$$P = 2\pi R/v \tag{2}$$

This can then give us the angular velocity of the satellite:

$$\Omega_{sat} = 2\pi/P \tag{3}$$

To calculate the size of the footprint D, recall that (applying the small angle approximation:

$$D = Rtan(\theta) \tag{4}$$

To calculate the decay in height per orbit, use the following equation:

$$\delta R \approx 4\pi d A \rho_{air} R^2/m \tag{5}$$

where d is the drag coefficient, A is the cross-sectional (along track) area of the satellite, ρ_{air} is the atmospheric density at the altitude of the satellite, R is the radius of rotation (R_E+ orbit height), and m is the mass of the satellite (sensor plus platform). The drag coefficient is the most uncertain value - use an estimate of unity. The cross section of the satellite can be inferred from Figure 1 (from the text by Stephens, 1994), and the density of the atmosphere at different heights is given in the table in Figure 2, taken from a 1959 Nature paper by Groves. Given the calculated period, how much does the orbit decay per year?

4. SENSOR

Considering what you want to measure, decide which sensor(s) might be right for the job. The following table should offer you some guidance regarding a few different sensors, what they're capable of measuring, the relative precisions of the sensors, and the approximate cost.

Note that the figures in this table are grossly simplified: the precision of each sensor changes greatly with respect to species, for example. It's only meant to provide some guidance.

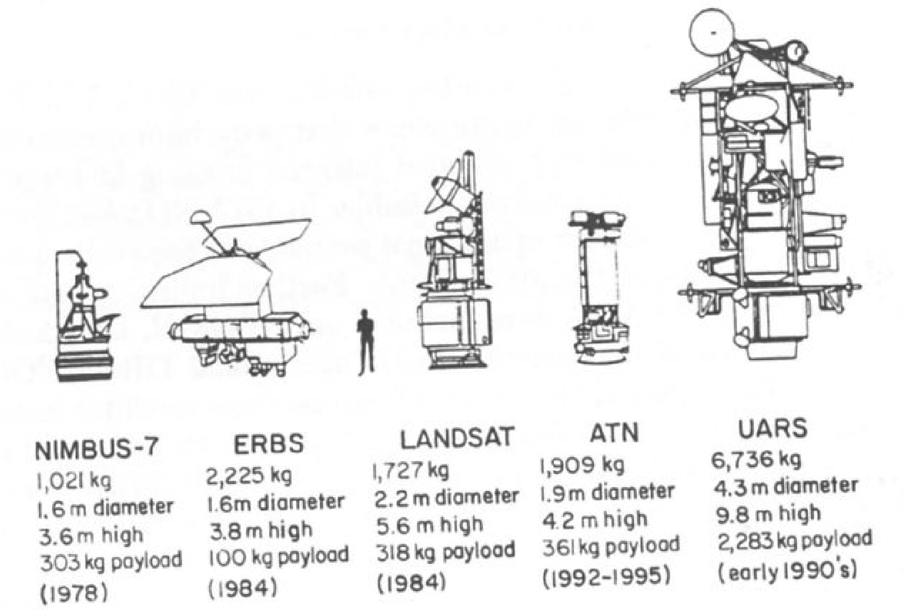

FIGURE 1. Dimensions of some satellite platforms.

Table 1. VALUES OF AIR DENSITY DERIVED FROM OBSERVATIONS ON SATELLITES 1957 α_2, β AND 1958 α, β_2, γ AND ε

Height (km.)	Air density (gm./c.c.)	Height (km.)	Air density (gm./c.c.)
150	$1{\cdot}2 \times 10^{-12}$	450	$3{\cdot}8 \times 10^{-15}$
200	$3{\cdot}8 \times 10^{-13}$	500	$1{\cdot}9 \times 10^{-15}$
250	$1{\cdot}4 \times 10^{-13}$	550	$9{\cdot}6 \times 10^{-16}$
300	$5{\cdot}0 \times 10^{-14}$	600	$5{\cdot}3 \times 10^{-16}$
350	$2{\cdot}0 \times 10^{-14}$	650	$3{\cdot}2 \times 10^{-16}$
400	$8{\cdot}4 \times 10^{-15}$	700	$2{\cdot}0 \times 10^{-16}$

FIGURE 2. Table of observed atmospheric density at various altitudes.

5. PLATFORM AND LAUNCH VEHICLE

This section is more technical than scientific, however it helps explain why satellites are so tremendously expensive. Table 2 presents some options for launch vehicles, and Table 3 presents some options for the platform on which the sensor should fly.

6. SPECIAL CASES

This is just to encourage you to think beyond replicating already existing satellite missions. For example, does it make sense to put other sensors on board the same platform to more completely answer your question? For instance, is there benefit to

TABLE 1. Sensors

Sensor	passive grid spectrometer	FTIR	DIAL	imager
IFOV (degrees)	1	1	0.008	0.2
Relative precision	1.0	1.5	1.3	1.5
Risk of failure (percent)	5	10	25	15
Development cost (M$)	100	200	200	250
Building cost (M$)	5	10	25	30
Weight (kg)	100	200	500	300
Power (W)	100	300	2000	500
Lifetime (years)	10	5	3	5
Special	one spectrometer per species	simultaneously CO_2, CH_4, N_2O, CO	day and night	128×128 sensors, CO_2 and CH_4

TABLE 2. Launch vehicles

Type	Payload (kg)	Cost (M$)	Orbit	Risk (%)
Ariane 5	10 500	120	GTO	5
Ariane 5	21 000	120	LEO	5
Falcon 9	13 000	61	LEO	10
Falcon Heavy	50 000	90	any	10
Falcon Heavy+	64 000	150	any	10
Delta IV Heavy	29 000	350	LEO	10
Delta IV Heavy	14 000	350	GEO	10
Start-1 ICBM	400	5	LEO	10
Experimental	5000	0	any	30

TABLE 3. Platform

Type	Weight (kg)	Max power (W)	Total cost (M$)
small	100	200	20
Envisat	10 000	2500	300
piggyback	1000	500	30

co-locating a laser DIAL with another instrument measuring the same thing in order to improve the measurement? Alternately, does it make sense to launch several (perhaps smaller) satellites to have a constellation in orbit? Consider the added costs (and benefits) of a constellation. (Note that the R&D costs don't have to be multiplied, and the satellites might be able to share a launch vehicle, but not a platform.)

7. Acronym

Necessary for all satellite missions, you should choose a clever acronym. The better the acronym, the better your chances of making it past the first round of project proposals!

8. Budget

Based on the numbers provided (or better numbers you may be able to find online), estimate the cost of your mission. How does this compare to the cost of existing missions? How about to the cost of monitoring the species in question from the ground?

9. Presentation

Present your mission to the group. This need not be a fancy presentation with graphics or slides, simply lay out the choices you made, and how you came to these choices.