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Abstract

The study by Mitchell and O'Brien (1987) demonstrated the feasibility of remote sensing of surface pressure based on analysis of the oxygen A-band as observed in sunlight reflected from the sea. In this paper, the results of the earlier work are used to map the regions on the sea where the technique should allow retrieval of pressure with an accuracy of 2 hPa. The regions are shown to be extensive and to be rather insensitive to the surface wind speed.

1 Introduction

The measurement of atmospheric pressure from space is one of the major unsolved problems of remote sensing of the environment and has attracted continued interest over the years. One of the earliest contributions was made by Hanel (1961), who suggested that the absorption of radiation by a gas well mixed in the atmosphere could be used to determine the mass of gas in a vertical column, and thence the atmospheric pressure. As candidates for the gas and the absorption band, Hanel proposed CO_2 and the molecular vibration band at 2 μm, but Yamamoto and Wark (1961) pointed out the advantages of oxygen and its absorption band at 760 nm (Fraunhofer's A band), namely, the virtual absence of atmospheric emission and the fact that few other atmospheric species absorb in the A band. The promise of a significant advance in observational meteorology led to experiments on Gemini-5 in which astronauts pointed a hand held radiometer tuned to the oxygen A band at selected clouds, while support teams in aircraft scrambled to locate the clouds and measure the pressure at the top. These experiments were reported by Saiedy, Jacobowitz and Wark (1967).

The feasibility of active remote sensing of pressure with lidar was first investigated by Smith and Platt (1977). Their study was impeded because none of the lasers available at that time could easily be tuned to the A band. Nevertheless, they concluded that profiling of both pressure and temperature appeared possible, provided the problems associated with laser stability and eye safety could be overcome. Subsequent development of Alexandrite lasers, which can be tuned to the A-band, has overcome some of the difficulties noted by Smith and Platt. Indeed, a laboratory based prototype has been developed by Schwemmer *et al* (1987) and the long term future of remote sensing of pressure undoubtedly lies with such instruments, once the technical difficulties of laser stability and power have been overcome.

Peckham, Gatley and Flower (1983) examined the possibility of using an active microwave system based on the 60 GHz absorption band of oxygen instead of the A band. After careful analysis of the errors anticipated for a microwave instrument, they concluded that surface pressure could be recovered with an accuracy of 1 hPa, even in adverse weather conditions such as thick cloud.

In the short term, however, passive instruments offer considerable promise and several proposals have been made recently. Curran et al (1981) developed an airborne, multichannel radiometer with two channels at 760.9 nm and 763.1 nm, with spectral resolution 1.4 nm, specifically intended for monitoring cloud top pressure. Wu (1985) investigated retrieval algorithms for Curran's data. Similar channels are planned for the MODIS instrument on the polar platforms. Barton and Scott (1986) questioned the feasibility of using absorption in the A band to measure pressure not only at cloud top but also at the surface. They constructed a simple, but elegant, radiometer with a single interference filter inclined to the optic axis, so that the passband (0.6 nm) of the radiometer swept across the A band as the filter rotated about its axis. Barton and Scott tracked the mass of oxygen in the solar beam as the sun moved across the sky in the course of the day and demonstrated that the oxygen mass could be monitored with an accuracy of 2 hPa.

All passive remote sensing techniques which use absorption of *reflected* sunlight in the A band to monitor surface pressure share a common problem, namely, that radiance scattered in the atmosphere generally traverses a shorter path than radiance reflected from the surface, so the scattered radiance suffers less absorption and leads to an underestimate of the surface pressure. Mitchell (1987) made an assessment of the impact of scattering upon Barton and Scott's proposal and concluded that retrieval of surface pressure was only feasible if the reflected radiance dominated the scattered radiance. This would be the case, for example, if the radiometer were pointed at areas of sunglint on the sea surface. Mitchell's finding was reinforced in a further, more extensive study by Mitchell and O'Brien (1987). An important point which emerged from the latter paper was that *the two components of the radiance, reflected and scattered, could be resolved if the A band were analysed with sufficiently high spectral resolution.* Mitchell and O'Brien concluded that remote sensing of surface pressure is feasible, provided that:

1. the surface is sufficiently bright;
2. the spectrograph used to analyse the A band has high spectral resolution (better than 0.05 nm), sufficient to analyse the structure of individual lines;
3. the instrumental noise can be kept below 0.1%;
4. the temperature profile can be ascertained from ancillary instrumentation to an accuracy of 2 K;
5. the total aerosol optical thickness can be determined to within an accuracy of 10%.

The first condition will be met over snow or regions of glint on the sea, but the remaining conditions are difficult to achieve, because the narrow spectral bandwidth limits the signal strength and signal to noise ratio, because retrieval of the temperature profile is in itself a difficult task, and, most importantly, because remote sensing of aerosols is notoriously difficult. Nevertheless, there is reason for optimism because new instrumentation such as the Advanced Microwave Sounding Unit (AMSU) aims to measure the temperature profile with the requisite precision, and the superior spectral coverage and spectral resolution of instruments planned for the polar platforms ought to allow determination of the aerosol loading with the 10% precision called for by Mitchell and O'Brien.

Accordingly, CSIRO is building a precision spectrograph to test the model predictions experimentally on the Fokker F27 research aircraft maintained by CSIRO. The spectrograph has excellent mechanical and thermal stability, high spectral resolution (0.025 nm), and high signal to noise ratio (10000:1). It is planned to fly the instrument, known as the Atmospheric Pressure Scanner (APS), over the sea and to scan in a plane which passes through the point of specular reflection in order to maximise the ratio of reflected to scattered radiance.

As part of the feasibility study for APS it is important to ascertain the potential coverage of the instrument when deployed on a satellite platform and to determine the time of the ascending node of the orbit for optimum coverage of the southern oceans, where conventional surface observations of pressure are sparse. The results of these calculations are presented in this paper. The satellite orbit is assumed to be similar to that of NOAA 9 and the zones of feasibility are shown as functions of season and time of the ascending node. It will be seen that the zones of feasibility are extensive and that the boundaries of the zones are not particularly sensitive to surface wind speed.

2 Feasibility zones

The radiance I^{sat} measured at the satellite can be resolved into the following components:

$$I^{sat} = I^{sea} + I^{atm},$$

where:

- I^{sea} is the radiance reflected from the sea without scattering in the atmosphere;
- I^{atm} is the radiance scattered at least once in the atmosphere.

The first term can be written in the form

$$I^{sea} = (4\pi)^{-1} r \sec\theta \int_0^\infty d\nu\, \Phi(\nu) F(\nu) exp[-ml(\nu)],$$

where:

- $F(\nu)$ is the extraterrestrial solar flux density at frequency ν;
- $\Phi(\nu)$ is the transfer function of the instrument at frequency ν;
- $l(\nu)$ is the vertical optical thickness of the atmosphere at frequency ν;
- θ and ζ are the satellite and solar zenith angles, respectively;

- m is the airmass of the atmosphere, defined by

$$m = \sec\theta + \sec\zeta\,;$$

- r is the bidirectional reflection coefficient of the sea.

According to Cox and Munk (1954) and Wagner (1967), r may be modelled in the form

$$r = \sigma^{-2}\sec^4\chi\, exp[-\sigma^{-2}\tan^2\chi] f(\alpha)\Lambda,$$

where:

- χ is the angle between the local normal vector and the normal to the plane which produces specular reflection from the sun to the satellite;
- α is the angle of incidence of the sun's rays onto this plane;
- σ^2 is the variance of the slope distribution on the sea;
- f is the Fresnel reflection coefficient for sea water;
- Λ represents the effects of shadowing on the sea surface.

Cox and Munk found experimentally that the variance of the surface slope distribution is linearly related to surface wind speed, w:

$$\sigma^2 = aw + b,$$

where empirically

$$a = 5.12 \times 10^{-3}\ \mathrm{m^{-1}s}\ , b = 3 \times 10^{-3},$$

if w is measured in units of ms^{-1}.

The numerical simulations carried out by Mitchell and O'Brien indicated that the bidirectional reflection coefficient r had to exceed a minimum value of 0.2 if the surface pressure is to be retrieved with an accuracy of 2 hPa. Consequently, the scan proposed for a satellite version of APS is directed towards sunglint and lies in the plane containing the satellite, the sun, and the point of specular reflection on the surface of the earth. This geometry, illustrated in figure 1, requires two axis control of the scan mirror during flight.

Figure 2 shows the zones where the reflection coefficient exceeds the minimum of 0.2 at the times of the solstices and equinoxes. Also shown are the tracks of the sub-satellite point, the specular reflection point and the horizon. As expected, the zones lie on the sunward side of the satellite track. The orbit parameters assumed for the calculation of the zones are similar to those for the NOAA 9 satellite, as tabulated below.

ascending node	1400	local solar time
orbit period	101	minutes
orbit inclination	99	degrees
orbit eccentricity	0	
orbit semi-major axis	7200	km

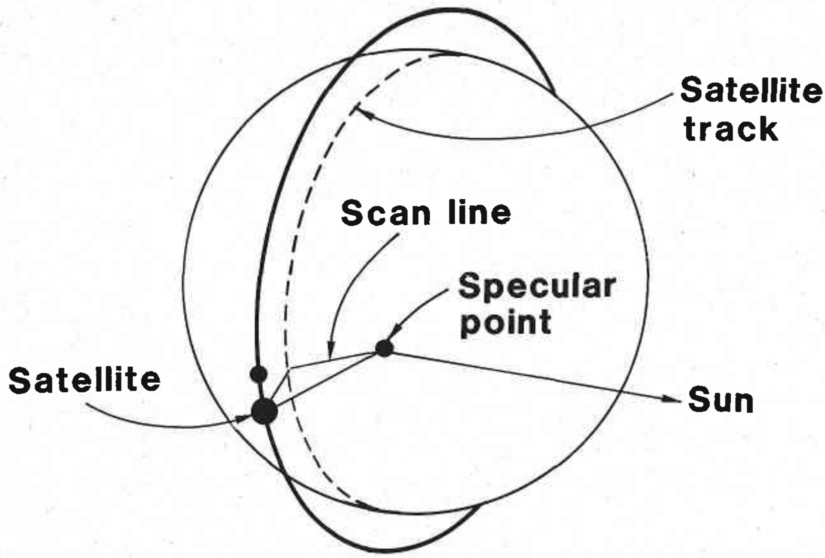

Figure 1: Scan geometry. The instrument scans in the plane containing the satellite, the sun and the specular point on the surface of the earth.

Figures 3, 4 and 5 are similar, except that the times of the ascending nodes are 1500, 1600 and 1700 hours local solar time respectively.

The bidirectional reflection coefficient of the sea depends upon the roughness of the sea, and hence upon the surface wind speed, for which a value of 2 ms^{-1} has been assumed in the calculations leading to figures 2 to 5. However, the reflection coefficient of the sea rises so rapidly near the sunglint region that the boundaries of the feasibility zones vary slowly with surface wind speed. This is illustrated in figure 6, which shows the zones for a surface wind speed of 4 ms^{-1} and an ascending node at 1600 hours local solar time.

These calculations show that:

- there are extensive zones over the sea where retrieval of surface pressure is feasible;
- the zones extend as the sun moves closer to the horizon, so later overpass times are well suited to APS;
- the zones are rather insensitive to the surface wind speed;
- the zones are larger in the winter hemisphere than in the summer hemisphere.

An example of the achievable daily coverage at the time of the September equinox is shown in figure 7. The orbit again is similar to that for NOAA-9 with an ascending node at 1600 hours local solar time. In the southern hemisphere coverage is complete from 48S to the Antarctic continent. This is significant given the potential importance of regular pressure soundings over the southern oceans for forecasting and climate modelling.

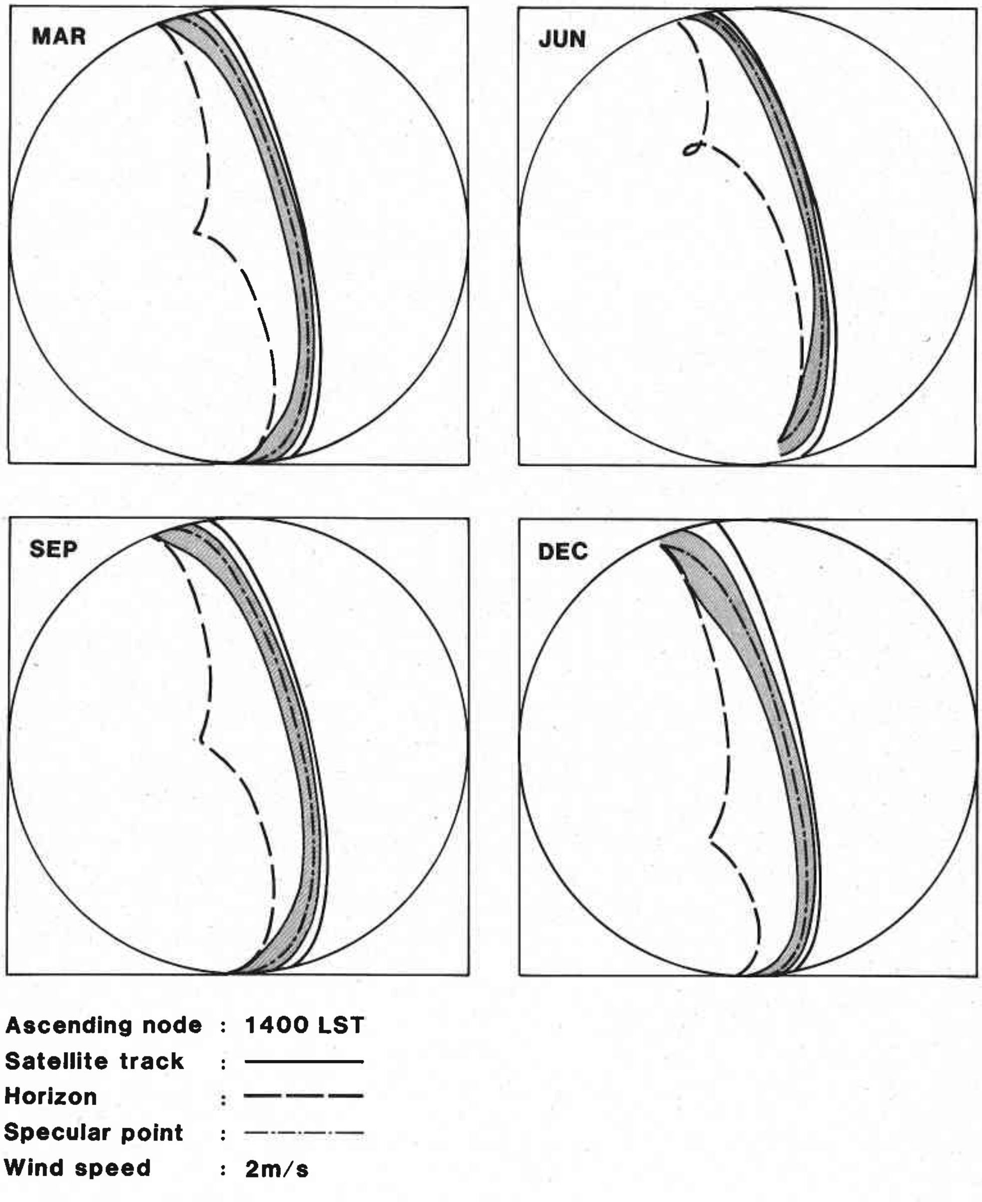

Figure 2: Zones where retrieval of surface pressure with an accuracy of 2 hPa appears feasible. The zones are shown at the solstices and equinoxes. Time of the ascending node is 1400 hours local solar time. The surface wind speed is assumed to be $2ms^{-1}$.

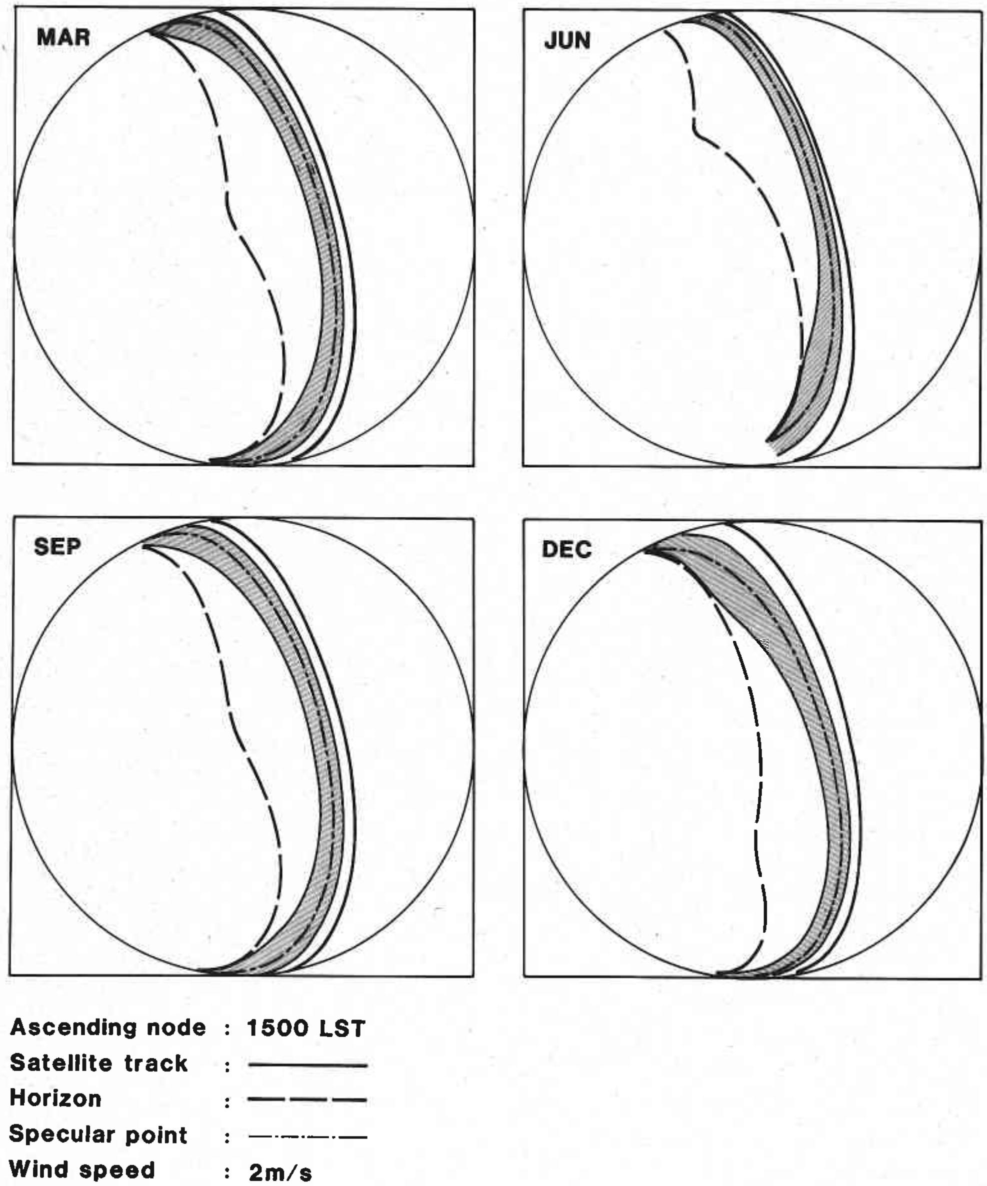

Figure 3: Same as for figure 2 except that the ascending node is 1500 hours local solar time.

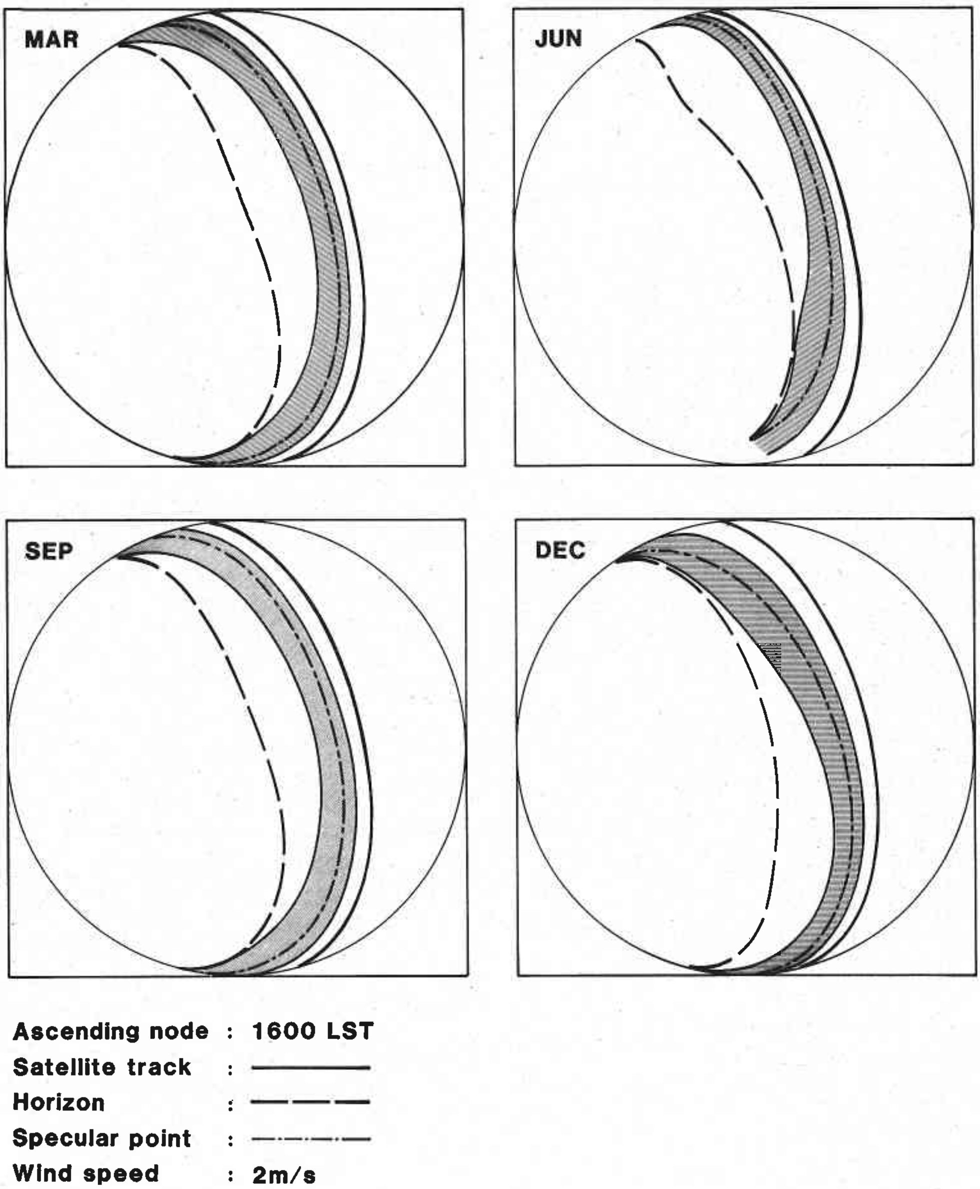

Figure 4: Same as for figure 2 except that the ascending node is 1600 hours local solar time.

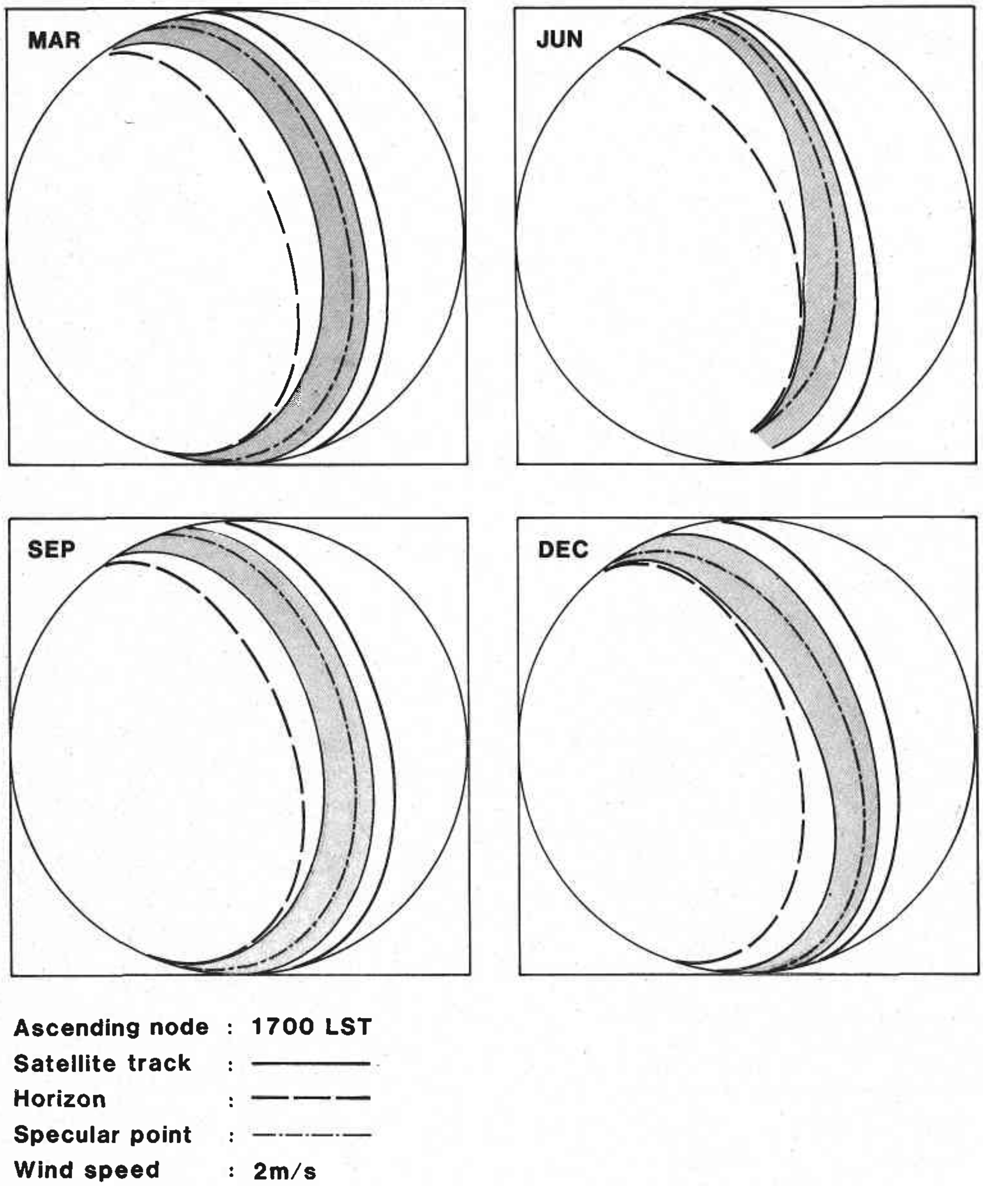

Figure 5: Same as for figure 2 except that the ascending node is 1700 hours local solar time.

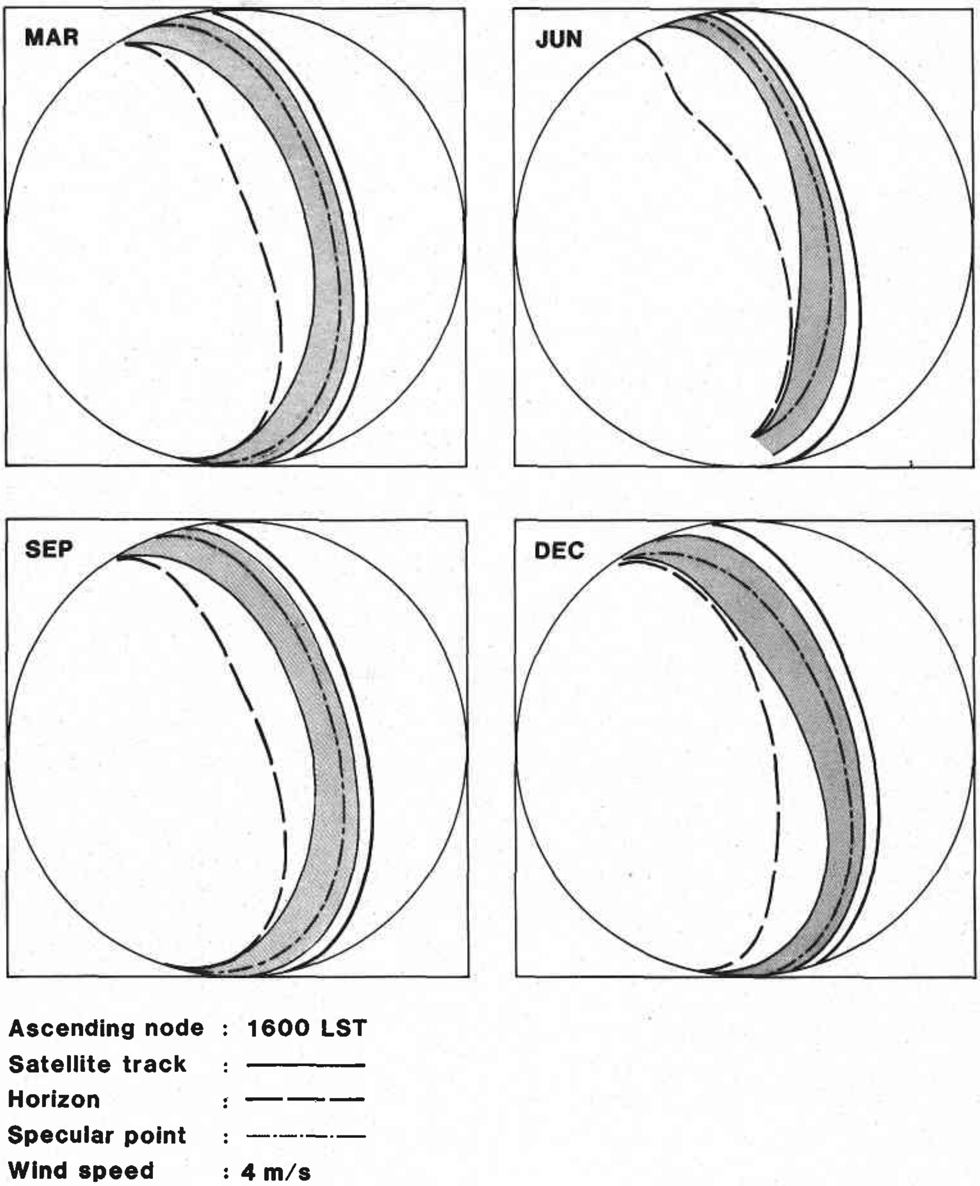

Figure 6: Same as for figure 2 except that the ascending node is 1600 hours local solar time and the surface wind speed is assumed to be $4ms^{-1}$.

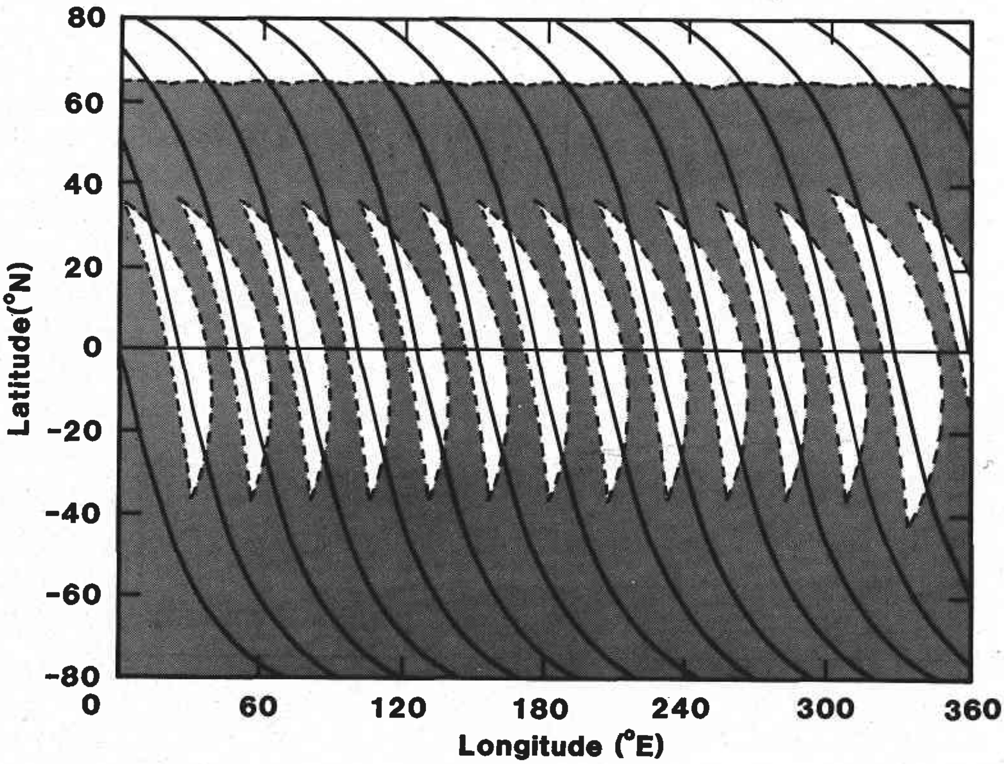

Figure 7: Global feasibility map.

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