Progress in remote sensing of vegetation chlorophyll fluorescence

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Abstract: Chlorophyll fluorescence (CF) has become a powerful tool in plant photosynthesis research and stress detection. These types of methods have been mostly relegated to the laboratory. Recently much attention has been paid to chlorophyll fluorescence sensing for the remote estimation of plant physiological status. Remotely sensed chlorophyll fluorescence emission has a potential to become one of the major global-scale reporter signals on vegetation performance and stress. In this paper, firstly, laser induced fluorescence sensing was presented, including a brief introduction, plant fluorescence spectral characters and some applications for stress detection. An overview was then given to the developments of solar induced fluorescence sensing, including methodology for the retrieval of vegetation CF from apparent reflectance (vegetation indices and FLD) and applications for monitoring plant health. Finally, the future development trends and the prospect of active and passive remote sensing of chlorophyll fluorescence were discussed.

Key words: chlorophyll fluorescence, remote sensing, vegetation

CLC number: Q14/TP79 Document code: A

1 INTRODUCTION

Photosynthesis is the most important biological process on earth. It is the unique approach by which plants gain energy from the environment. There are three basic effects when light strikes a leaf surface: absorption, reflection and transmission. The major part of light is absorbed by the chlorophyll used for photosynthesis, and only a small proportion is de-excited via emission with a longer wavelength as fluorescence, or dissipation as heat.

Chlorophyll fluorescence emissions occur in the red and far-red regions of the plant spectrum (650—800 nm). Numerous studies showed that CF is considered a rapid, highly sensitive and non-invasive probe of photosynthetic activity and could be a useful tool to monitor plant response to the environment (Krause & Weis, 1991; Maxwell & Johnson, 2000). CF signature is determined not only by plant physiological and biochemical characteristics but also by environmental factors, such as light intensity, excitation light wavelength, radiation spectral component, temperature and humidity (Agati, 1998; Zarco-Tejada et al., 2006).

There are three kinds of techniques to study CF: chlorophyll a fluorescence induction kinetics, laser induced fluorescence and solar induced fluorescence. Presently chlorophyll a fluorescence kinetics technique has been widely applied to many fields, such as plant physiology, plant nutrition and plant ecology. Modulated or non-modulated fluorometers were used for measurement. Among them PAM-2100 (Walz, Germany) and FMS-2 (Hansatech, England) were widely used. The technique principle was similar. Many parameters could be derived under dark or light condition from different light source analysis: measuring light, actinic light, saturation pulses and far-red light (Maxwell & Johnson, 2000). CF induction kinetics technique is a useful tool to explain photosynthetic mechanism, but it is a contact measurement. The disadvantage of such CF measures is the fact that they provide only limited information on the state of health of plants, as a single leaf spot is often less representative and much sensitive to environment. Scientists were looking for new approaches that fluorescence could be remotely and rapidly recorded.

The use of chlorophyll fluorescence has been extended to remote sensing of terrestrial vegetation for more than thirty years. A number of research groups were interested in active laser induced fluorescence (LIF) technology, which could offer fluorescence excitation spectra of the target. When plant were excited by UV light source (320—380nm), fluorescence emission spectra were then detected by the instruments. It was suggested that vegetation fluorescence spectral properties (intensity, shape and intensity ratio of different bands, etc.) were determined not only by the instruments (excitation wavelength and S/N, etc.) but also by pigment composition, pigment content...
and plant biomass. So laser induced fluorescence was a good indicator of photosynthetic performance of plants (Shen et al., 2002). But Rosema and Zahn (1997) argued that LIF sensing had some limitations when measured at large scale. In recent years many studies suggested that solar induced fluorescence (SIF) was currently the most promising approach towards space platform (Plascyk & Gabriel, 1975; Carter et al., 1996). Although solar induced chlorophyll fluorescence signal was very weak, its detection was possible using vegetation indices and solar Fraunhofer line discrimination (FLD) methods from plant apparent reflectance. Nowadays, Fluorescence Explorer (FLEX), as one of the six new Earth Explorer missions made by ESA in 2006, is dedicated to monitoring spatio-temporal variations of photosynthetic efficiency from space and better modeling of regional carbon fluxes (Rascher, 2007). FLEX will carry a very high-spectral resolution imaging spectrometer that allows the weak fluorescence signal to be decoupled from the reflected sunlight background. Secondary instruments will observe other variables such as vegetation temperature, which together with the fluorescence observations will allow for the assessment of light-use efficiency and exchange of carbon between plants and the atmosphere. During the recent past, research efforts were mainly for development of sensors (Carter et al., 2004) and research on radiative transfer modeling (Zarco-Tejada et al., 2006).

This paper reviewed and summarized the developments of laser induced fluorescence sensing (active) and solar induced fluorescence sensing (passive) technologies, with the aim of attracting much domestic attention for further research.

2 LASER INDUCED FLUORESCENCE SENSING OF VEGETATION

2.1 Introduction

From the 1960s, with the rapid development of laser technique and photo-electric detection for weak signal, laser induced fluorescence technology has been widely applied to many fields such as analytical chemistry, environmental control, remote sensing of water body and vegetation. The features of LIF were as follows: (1) abundant information contained; (2) fluorescence spectroscopy directly related to fluorescent substance type, concentration and molecular energy levels structure; (3) fluorescence spectroscopy was sensitive to plant growth environment. Laser induced fluorescence of green plants was first evaluated by Chappelle et al. (1984) as a means of remotely detecting plant stress and determining plant type. Then many researches on LIF progressed. Fluorescence imaging sensing system has been made by NASA for monitoring photosynthesis and primary productivity in terrestrial ecosystem at regional and global scales. In China, some basic works were collaborated by two groups of Chinese Academy of Sciences (Anhui Institute of Optics and Fine Mechanics and Institute of Soil Science), using setup laser fluorescence lidar system to study the potential application on soil and plant in 1980s.

2.2 Laser induced fluorescence technique

This subsection provides a brief introduction to physical principles of fluorescence and LIF techniques. A laser beam is used to excite the specie (a molecule or atom) of interest. By absorbing the laser beam photons, the specie transition from a ground electronic state to a short-lived excited electronic state. In order to return to a stable ground state the molecule can release the extra energy through emit a photon, namely fluorescence (Sun et al., 2003). Fluorescence emission always occurs at wavelengths longer than the excitation wavelength. Fluorescence spectra directly reflect information of molecular structure. Fluorescence emission spectral properties can be described as distribution, peak intensity and line width. Under the same excitation condition, different energy level structures result in different fluorescence emission spectral properties. This method proved very useful in substance investigation (Desevaux et al., 2002).

Fluorescence emission spectra of green plant were excited by UV light (λ<380 nm) in LIF technique. Nitrogen laser and Nd:YAG laser were commonly used as light sources. Emission fluorescence spectra could be detected by optical system and analyzed by the computer. With the development of spectral imaging technology, many countries established laser induced fluorescence imaging system, which could provide ample fluorescence information of many ten thousand pixels over the whole leaf area. Thus it allowed detection of spatial variability and early detection of plant stress in fluorescence emission (Buschmann et al., 2000). The main advantage of active fluorescence sensors compared to passive sensors is the possibility of measurement almost independent of light conditions, perhaps even during the night. Presently LIF technology is mainly applied for marine biology and environment monitoring. Most of LIF studies on vegetation remain at leaf and canopy level, and research on vegetation monitoring by LIF from aerial or satellite platform is rarely seen.

2.3 Laser induced fluorescence spectra of vegetation

When plant leaves are excited by short wavelength light, fluorescence is emitted. Fluorescence spectra vary in plant species and physiological properties. The typical spectrum of a green leaf is characterized by three bands with maxima near 440nm (blue), 685nm (red), and 740nm (far-red) (Fig. 1). Some species also emit fluorescence in green region centered at 525nm or 550nm. Specially, chlorophyll fluorescence emission spectrum is in the 650—800nm wavelength range, centered at 685nm and 740nm. It is well known that red fluorescence comes primarily from chlorophyll a of PSII, while far-red fluorescence comes from PSI and PSI (Agati et al., 2000). Blue-green fluorescence emission was thought to represent a mixed signal from compounds of multiple origin, namely,
NADPH, a semiquinone which is most likely vitamin K and xanthophylls (Chappelle et al., 1993). From fluorescence imaging Lichtenthaler et al. (1996) proved that the major part of the leaves’ blue and green fluorescence was emitted from the main and side leaf veins, whereas the major part of the leaves’ red and far-red chlorophyll fluorescence was emitted from the vein-free leaf regions.

![Fluorescence spectrum excited at 355nm](image)

**Fig. 1** Vegetation spectral reflectance and fluorescence emission spectrum excited at 355nm

### 2.4 Applications of LIF sensing in plant stress detection

Drought or nutrient deficiency will result in decrease in pigments (chlorophyll and carotene) content; this can be detected by measurement of reflectance and fluorescence (Lichtenthaler et al., 1996; Gitelson et al., 1996). Specially, Heisel et al. (1996) found that LIF could be useful tool in early detection of stress, as changes in fluorescence (chlorophyll function) often preceded changes in chlorophyll content. The plant status was characterized by the fluorescence emission intensities and fluorescence ratios. Fluorescence intensity in blue band could reflect energy transmission efficiency of pigment in shortwave band, while $F_{440}/F_{730}$ could reflect information about how energy was distributed between PSI and PSII. For example, Wang et al. (1996) found Potassium deficiency could result in increases of fluorescence intensities at 440nm, 550nm and 680nm, while decrease in the fluorescence ratio $F_{440}/F_{530}$. Lichtenthaler and Miehe (1997) have proposed that fluorescence images and the corresponding fluorescence ratio images $F_{440}/F_{530}$, $F_{440}/F_{730}$ and $F_{530}/F_{730}$ were sensitive to environmental change and stress, and could be used to assess the photosynthetic activity of leaves, to monitor the uptake of herbicides by plants, to screen for mineral deficiencies or as a general indicator of plant stress. Corp et al. (2003) have developed two active fluorescence sensing systems in leaf level and canopy level. The latter could simultaneously acquire four band images of plant canopies under ambient sunlight conditions, and the results indicated that significant relationships exist between nitrogen supply and in vivo fluorescence emissions from corn leaves.

Former studies also showed that laser induced fluorescence was sensitive to plant water deficit. Cerovic (1996) simultaneously measured diurnal changes of the mean lifetime and yield of CF, at distance using a τ-LIDAR and a Modified PAM. The results showed that water stress effects on fluorescence changes were different in plant types and irradiance. Lichtenthaler and Babani (2000) showed that different parts of the leaf photosynthetic activity under water stress could be detected using fluorescence imaging system. Fluorescence band ratios blue/red and red/far-red could also reflect plant water status. Subhash and Mallia (2003) measured pant fluorescence spectra with He-Ne laser during the initiation and recovery phases of water stress, demonstrated that $F_{685}/F_{730}$ ratios increased along with water stress, and then recovered to some extent on removal of stress.

To sum up, compared with modulated fluorometers which could only obtain point data, laser induced fluorescence technology, especially imaging fluorescence technology could provide large-scale and more comprehensive information about early detection of plant stress. In order to obtain most accurate spectral information, various factors should not be neglected, such as effects of background and atmosphere, selection of fluorescence band or excitation wavelength, and feasible monitoring time. In a recent study Ounis et al. (2001) argued that the minimum pulse energy needed to detect chlorophyll fluorescence from a space platform at 400 km would be in the order of several tens Joules per pulse. At the present time, the use of such a powerful laser from space seems unrealistic.

### 3 REMOTE SENSING OF SOLAR INDUCED FLUORESCENCE OF VEGETATION

#### 3.1 Introduction

Previously described LIF is an active remote sensing technique using laser light. Under natural sunlight illumination, the chlorophyll fluorescence can also be emitted by the vegetation. Passive detection of fluorescence signal may be used to estimate plant functioning, stress and vitality. In 1998 FLEX (Fluorescence Explorer) mission was proposed in response to ESA call for Earth Explorer Opportunity missions. FLEX intends to explore the possibility for passive measurements of natural sunlight-induced fluorescence, with the aim of improving estimates of vegetation photosynthetic activity and its implications for surface carbon fluxes estimation. Then in 1999 a similar mission FLEXSAT was proposed by NASA (Stoll et al., 1999). From 2002, ESA has funded a series of experiments to observe the solar induced fluorescence signal in Finland (Moya et al., 2004). Although studies on remote sensing of solar induced fluorescence of vegetation still stay at the early stage, more and more scientists gave their attention to it recent years. So far three international conferences about vegetation fluorescence sensing have been held (2004, 2006, 2007). In China only a little work were explored (Liu et al., 2006; Zhang et al., 2007a).

Fig. 2 shows the scheme of distribution of the energy of...
photos of sunlight incident on a green leaf, including generation of fluorescence. The sun is the most commonly used source of energy for passive remote sensing. There are three forms of interaction that can take place when energy strikes upon the leaf surface: absorption, transmission and reflection. The amount of light distribution by a leaf largely depends on epidermal characteristics, anatomical characteristics, and the pigment composition. Among them, about 48%—94% of PAR can be absorbed by the leaf. This energy is used for photochemistry (i.e., photosynthesis), dissipated as heat, or re-emitted as fluorescence.

![Fig. 2](image)

**Fig. 2** Different processes occurring to the energy reaching leaf surface (Vidaver et al., 1991)

In the next sections two kinds of detection methods on solar induced fluorescence are introduced. One can be called indirect method based on estimation of spectral indexes that are sensitive to fluorescence. The other can be called direct method based on Fraunhofer line discrimination.

### 3.2 The indirect methods—based on spectral index estimation

Nowadays reflectance spectra are the main optical signatures used for vegetation monitoring. However, changes in the reflectance signature appear only after serious damage of the bio-systems has occurred. With respect to reflectance, fluorescence is more specific as an observable of the basic biophysical processes in the plant cells. The effect of chlorophyll fluorescence emission on the apparent reflectance spectrum has been investigated recently. Evidence of a solar-induced fluorescence signal superimposed on leaf reflectance signatures was first reported by Buschmann and Lichtenthaler (1998). Then CF spectra were successfully observed from reflectance of maple leaf (Zarco-Tejada et al., 2000a), wheat leaf (Zhang et al., 2005) and maize leaf (Zhang et al., 2007b) using an integrating sphere coupled to a spectrometer. The observed CF spectral signature was similar with that of laser induced fluorescence. Along with the development of sensors, using a very high spectral resolution subnanometer featuring full width at half maximum of 0.06nm, a characteristic peak superimposed on the reflectance at 687nm and 760nm was proved to be affected by fluorescence emission (Meroni & Colombo, 2006). The most recent work (Entcheva Campbell et al., 2008) has shown that the relative contributions of CF to apparent reflectance were 10%—20% at 685nm and 2%—6% at 740nm.

The red-edge region (from 650 to 800nm) of vegetation spectra contains information about the molecular structure of the plant’s cells, and has been widely used in studies to estimate chlorophyll concentration, biomass and LAI (Huang et al., 2004; Mutanga & Skidmore, 2007). Besides, chlorophyll emits fluorescence within the range of the red-edge, so both contributions (chemical structure and fluorescence) are mixed. Recently, many spectral indices related to fluorescence were constructed, such as $R_{575} / R_{665}$, $R_{440} / R_{690}$, $R_{730} / R_{665}$, $R_{685} / R_{655}$, $R_{660} / R_{655}$ (Zarco-Tejada et al., 2000b). Moreover, Zarco-Tejada et al. (2003) demonstrated that natural fluorescence emission was observable from derivative reflectance as a double-peak feature in the red edge region. Derivative reflectance indices, like $D_{531} / D_{645}$, $D_{700} / D_{722}$, $D_{700} / D_{700}$, $D_{700} / D_{720}$, $D_{700} / D_{720}$, and $D_{427} / D_{437}$, were built to track steady-state fluorescence changes from canopy reflectance.

Besides, relations between PRI (photochemical or physiological reflectance index) and chlorophyll fluorescence were discussed. PRI was proposed at early 1990s and could be used as a direct index of photosynthesis. PRI was sensitive to the de-epoxidation of the xanthophyll pigment cycle and could be used to detect dynamic variations of non-photochemical quenching of chlorophyll fluorescence (Gammon et al., 1992, 1997). PRI was calculated as follows:

$$PRI = (R_{531} - R_{730})(R_{531} + R_{730})$$

where $R_{531}$ and $R_{730}$ represented respectively the reflectance at 531nm and the reflectance at 570nm.

When light exceeds the amount that can be used for photosynthesis (for example stress occurred), excess energy is dissipated to avoid photoinhibition and photooxidation. One of the mechanisms consists in the re-radiation of the excess energy as fluorescence emitted by chlorophyll a of photosystem 2. The other mechanism is heat dissipation, linked to inter-conversion of the xanthophylls cycle pigments, and inducing changes in the leaf reflectance at 531nm which are detected by PRI (Penuelas et al., 1994). Combination of 531nm (xanthophylls signal waveband) and 570nm (a reference waveband) can partly reduce the effect of other factors such as chloroplast movements that can affect reflectance in this spectral region, track instantaneous changes in photosynthetic light regulation at PSI, and partly correct for the complicating effects of sun angle, leaf movement and canopy architecture. Thus PRI provided a new method to estimate photosynthetic efficiency in the field of remote sensing (Penuelas et al., 1997; Rascher & Pieruschka, 2008).

Using vegetation index to estimate solar induced fluorescence can be regarded as an indirect method, which aims to find a consistent relation between spectral indices and fluorescence variables.
3.3 The direct method—based on Fraunhofer line discrimination (FLD)

Measuring the fluorescence of vegetation from space seems only possible by detecting solar induced fluorescence based on Fraunhofer line discrimination. Under natural sunlight illumination, the amount of chlorophyll fluorescence emitted by vegetation represents a very small fraction of the reflected light in the visible part of the spectrum. However, at certain wavelengths where the solar spectrum is attenuated (Fraunhofer lines), the fluorescence signal can be quantified. In the red and near infra-red part the solar spectrum three main absorption bands are present: the Hα band at 656 nm, which is due to absorption by the hydrogen of the solar atmosphere, whereas the two bands at 687 nm and 760 nm are due to absorption by the molecular oxygen of the terrestrial atmosphere. These bands largely overlap the chlorophyll fluorescence emission spectrum of leaves. Using FLD method we can obtain information on the fluorescence from the whole reflectance signal. This method compares the depth of the line in the solar irradiance spectrum to the depth of the line in the radiance spectrum of the plant to quantify what extent a Fraunhofer “well” is filled up relative to the continuum due to fluorescence energy (Elachi, 1987; Liu et al., 2005).

The principle of the FLD method is summarized and shown in Eqns. (2)–(5) and Fig. 3. The radiance of the target (plant) is compared to that of a reference panel situated in the same illumination condition. Parts a and b represent the detected irradiance from the reference panel in and out of the oxygen absorption feature, respectively. Similarly, c and d represent the detected radiance from the target at the border and at the bottom of the band. The output parameters are the reflectance coefficient (R) and the fluorescence flux (f) contributioning to the total target radiance. R is defined as the ratio between the energy flux reflected by the sample in a given solid angle and the energy flux reflected by the reference panel, for the same solid angle. According to Plascyk and Gabriel (1975),

\[
\begin{align*}
  c &= R \times a + f \\
  d &= R \times b + f \\
  R &= \frac{(c - d)}{(a - b)} \\
  f &= d - R \times b
\end{align*}
\]

(2) (3) (4) (5)

It should be noted that that R is obtained free of any fluorescence contribution. Once R is calculated, f can be deduced by subtracting the reflectance component to the total radiance of the target. Therefore, f is almost independent of the Fraunhofer line’s width, depth and shape if the spectral resolution and signal-to-noise ratio (SNR) is high enough, which means that atmospheric effects on Fraunhofer line can be neglected if the solar irradiance spectrum and the canopy reflected radiance spectrum are acquired synchronously. Fluorescence flux information at 687 nm and 760 nm calculated from FLD could be useful for detecting physiological status of plant (Liu et al., 2005).

Several sensors have been built to detect solar induced fluorescence based on FLD in recent years. For fluorescence measurements two spectrometer concepts have been considered by Smorenburg et al. (2002): an imaging spectrometer and a filter spectrometer. By adding interference filters (center wavelength was 656 nm, Hα Fraunhofer line) before CCD of a digital camera, Saito et al. (2003) developed a fluorescence imaging system for detection of plant fluorescence induced by sunlight. Moya et al. (2004) constructed a passive instrument measuring the in-filling of the atmospheric oxygen absorption band at 760 nm by chlorophyll fluorescence in France, which has been used at distances of up to 50m.

3.4 Applications of solar induced fluorescence technique for remote detection of plant stress

With the developments of new sensors and new methods in fluorescence detection, analyses of chlorophyll fluorescence, integrated with reflectance, physiological and biochemical characteristics, were widely used in monitoring plant functioning, stress and vitality.

(1) Nutrient stress monitoring. Zarco-Tejada et al. (2003) showed that natural fluorescence emission was observable on the derivative reflectance spectra as a double-peak feature in the 690—710 nm spectral region, which was mainly due to CF effects and pigment degradation. Middleton et al. (2003) showed a red edge first derivative ratio D_{max}/D_{744} was strongly related to chlorophyll content, photosynthetic rate, and C/N ratio, and could be used for species discrimination and nitrogen deficiency detection. McMurtrey et al. (2003) suggested that fluorescence in the apparent reflectance at 685 nm could distinguish nitrogen stressed corn from those with optimally applied nitrogen.

(2) Water deficiency detection. Zhang et al. (2006) demonstrated that CF peak ratio F_{685}/F_{740} was closely related to leaf water content and fluorescence parameters. Most studies (Penuelas et al., 1997; Winkel et al., 2002; Van Gaalen et al., 2007) suggested that drought resulted in PRI declined. At leaf level, PRI was positively related to F_{i}/F_{m}, ΔF/F_{m} and PRUE, but...
negatively related to NPQ (non-photochemical quenching). A new instrument capable of passive remote sensing of dynamic PRI changes was designed by Evain et al. (2004) for water stress detection at the canopy level and under field conditions. Suárez et al. (2008) demonstrated that the airborne-level PRI index was sensitive to the de-epoxidation of the xanthophyll pigment cycle caused by water stress levels compared to NDVI and TCARI/OSAVI. Namely among the three vegetation indices calculated, only airborne PRI demonstrated sensitivity to diurnal changes in physiological indicators of water stress. However, Gamon et al. (2002) argued that a consistent relation between PRI and radiation-use efficiency at the canopy level has not always been found, and PRI did not work well under the severe drought conditions.

(3) Other stress detection. Saito et al. (2003) developed a solar fluorescence imaging system to observe plant chlorophyll concentration, pigment species and disease, but its availability need to be further investigated. Moya et al. (2004) monitored the penetration of diuron, a herbicide acting on photosynthesis, by the passive instrument on a corn canopy at the range of 50m. The results showed that a good agreement was found between gas exchange and variable chlorophyll fluorescence at the canopy level. Zhang et al. (2007a) showed that solar induced fluorescence information based on FLD methods could be used for wheat stripe rust detection.

4 SUMMARY AND PROSPECTS OF REMOTE SENSING OF PLANT FLUORESCENCE

Chlorophyll fluorescence of vegetation gives specific information about factors such as stress and vitality and has a great additional value to the standard spectral reflectance measurements. Chlorophyll fluorescence analyses have become rapid, sensitive, non-destructive and non-intrusive techniques in photosynthesis research. The measurement of chlorophyll fluorescence induction kinetics has provided considerable information on the organization and function of the photosynthetic apparatus. However, further applications are restricted in the following: (i) at canopy level it is hard to acquire $F_v/F_m$ because plant need to be dark-adapted; (ii) measurement area is limited, which caused low representative; (iii) mainly use in the laboratory and is usually affected by environmental conditions in the field. While laser induced fluorescence technology can be used for large scale, with the advantages of high sensitive and selective. But preliminary estimations indicated that limited by pulse energy (Unis et al., 2001) and plant safe (Rosema & Zahn, 1997), it is not suitable for long range remote sensing. Solar induced fluorescence can be measured without artificial light, reflecting the real status of plant, and has the potential to be retrieved from air and space borne platforms. But further studies should be explored, such as correction of atmospheric effects, quantitative relationship between fluorescence variables and the environmental factors. These rely on the developments of quantitative remote sensing theory and technique, improvements of sensor performance, scaling-up fluorosensing from the leaf to the canopy. In conclusion, remote sensing of vegetation chlorophyll fluorescence especially natural fluorescence will attract more and more attentions and this technique will be widely applied in vegetation remote sensing, plant physiology, plant ecology and agricultural science.

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摘 要：

关键词：

中图分类号： Q14/TP79 文献标识码： A

1

1. (650—800nm)](Krause & Weis, 1991; Maxwell & Johnson, 2000)]

(800nm) (laser induced fluorescence, LIF). 320—380 nm (Agati,1998; Zarco-Tejada, 2006)]

E-mail: yongjiangzh@sina.com]
(Plaseyk & Gabriel, 1975; Carter, 1996) (solar induced fluorescence, SIF) (2006), (ESA) 6 (Rascher, 2007) FLEX (fluorescence explorer), (Plascyk & Gabriel, 1975; Carter, 2006), (Zarco-Tejada, 2006)

2.1  
20 60, 602.1 20 80, 802.2 20 525nm

2.3  
400—800nm 3 400—700nm, 700 3 525nm 550nm

![Graph]

650—780 nm, 488 nm, 685 nm, 740 nm, 2.4

2.4

Chappelle (1993) and NADP (1993) k. Lichtenthaler (1996). Lichtenthaler et al. (1996; Gitelson et al., 1996). F685/F740 = 0.536; F440/F685 = 0.228; 740 nm / 685 nm 2

440 nm / 550 nm / 680 nm

440 nm / 550 nm / 680 nm (Lichtenthaler, 1996; Lichtenthaler et al., 1997; F480/F685/F440/F750)

F685/F740 = 0.536; F440/F685 = 0.228; 740 nm / 685 nm 2

480 nm / 550 nm / 680 nm

480 nm / 550 nm / 680 nm (F685/F740)

Hartmut (2000)

He-Ne

F685/F730 0.00

Rfd / Ap

3

3.1
3.2 Fraunhofer (PAR), UV, FR and IR: 50%—60%.

Fraunhofer

PRI (photochemical reflectance index) PRI (physiological reflectance index)

PRI = (R_{351—R_{730}})/(R_{351}+R_{730})

PRI = (R_{351—R_{730}})/(R_{351}+R_{730})

3.3 Fraunhofer
3.4  

\[ R = \frac{D_{\text{max}}/P_{\text{max}}}{P_{\text{max}}} \]

\[ F = \frac{c - d}{a - b} \]

\[ d = R \times b + f \]

\[ c = R \times a + f \]

\[ f = c - R \times a \]

\[ R = (c - d)/(a - b) \]

\[ R = \frac{D_{\text{max}}/P_{\text{max}}}{P_{\text{max}}} \]

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