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Fraunhofer Filters to Reduce Solar Background for Optical Communications

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A wavelength that lies within a spectral interval of reduced solar emission (a Fraunhofer line) can carry optical communications with reduced interference from direct or reflected background sunlight. Suitable Fraunhofer lines are located within the tuning range of good candidate lasers. The laser should be tunable dynamically to track Doppler shifts in the sunlight incident on any solar system body that may appear in the background as viewed by the receiver. A Fraunhofer filter used with a direct-detection receiver should be tuned to match the Doppler shifts of the source and background. The required tuning calculated here for various situations is also required if, instead, one uses a heterodyne receiver with limited post-detection bandwidth.

I. Introduction

A. Sunlight Interference

Sunlight interferes with optical communications when it enters the receiver telescope and detectors. It may be scattered into the receiver from the blue sky, or it may enter as part of the background when the telescope is looking at the laser source. The sun itself may be in the background. If, instead, a planet or a moon appears in the background, the interfering light is still sunlight after reflection and scattering from the background surface.

B. Lines in the Solar Spectrum

No matter how the sunlight enters the receiver, it still has the spectrum of sunlight. In particular, there are many narrow wavelength intervals in which the sunlight is greatly reduced because of a natural filter existing over the sun. This filter consists of iron and other vaporized materials in the solar atmosphere above the photosphere (the visible surface of the sun). The region where these materials exist is called the "reversing layer" because the materials absorb rather than emit light at characteristic wavelengths, producing a spectrum that is the reverse of an emission spectrum. Each of the resulting intervals of low sunlight emission is called a "Fraunhofer line."

C. Discriminating Against Sunlight

A Fraunhofer filter is a very narrow optical filter that only admits light whose wavelength lies within a Fraunhofer line. Viewed through a Fraunhofer filter during the day, the sun, the sky and the ground look dark; at night all the planets and their moons look dark. A laser whose wavelength falls within the Fraunhofer line looks like one bright spot in the darkness, by day or by night.

A closer look through the filter shows that the limbs of the sun and the Jovian planets are bright near the equators, because of appreciable Doppler shifts caused by the high surface rotation velocities of those bodies. Also, at certain times the planet Mercury looks bright as it moves rapidly toward or away from the sun in its highly elliptical orbit. To remain visible, a laser that moves through the solar system should tune itself to the center of the Fraunhofer line as reflected by any object in the background. The Fraunhofer filter would have to be tuned accordingly.

As the earth moves in its orbit it also approaches or recedes from all these bodies. Therefore, as one looks through the filter and turns from viewing the sun to viewing other solar system bodies, one would need to tune the Fraunhofer filter to compensate for additional Doppler shifts.

D. Application

On any mission employing an optical data link to the earth, the chief interference may be sunlight, direct or reflected from a planet or satellite. An ideal sunfilter with a highly transmitting passband just wide enough to admit the laser signal would reduce solar background to tolerable levels. Sunlight admitted within the passband would continue to interfere, however.

If the laser wavelength were chosen to operate close to or within a Fraunhofer line, sunlight interference would be reduced further and communication would be improved. The greatest improvement would be realized by tuning the source laser to the minimum of a deep Fraunhofer line and narrowing the filter passband to lie entirely within the Fraunhofer line.

In reality the passband must either be wide enough to allow for all Doppler shifts to be encountered during the mission, or it must be tunable (or at least selectable) as the received signal wavelength changes.

There is also a trade-off in filter design between narrowness of the passband (to reduce background interference) and peak transmission (to maximize the received signal). It is not enough simply to maximize the signal-to-noise ratio; see Ref. 1.

E. Simplest Application

An optical communications system designer may choose a nontunable source laser for stability, reliability, and other reasons. The wavelength chosen for such reasons is unlikely to coincide exactly with a Fraunhofer line. Also, the receiver filter passband may be chosen as wide as 1 or 2 nm (10 or 20 Å) in order to obtain transmission of 70% to 80%. If these choices are made for a mission to an outer planet, the background of reflected sunlight when the planet fills the receiver field-of-view may be tolerable.

Even with these choices, however, the center frequency of the filter passband should still be chosen to take advantage of the existence of Fraunhofer lines. After all expected Doppler shifts of the received signal have been included, the filter passband should be chosen to include as many strong Fraunhofer lines as possible. Each included line could reduce background sunlight interference by 5% to 10%.

II. Fraunhofer Lines and Filters

A. Fraunhofer Lines

A high-resolution solar spectrum shows hundreds of dark lines. In some of them solar emission is reduced to 10% or less. Typical widths are 0.01 nm (0.1 Å). The center of the lines might be found to within an uncertainty of about 0.001 nm or 0.01 Å. (Since that uncertainty corresponds to 1 pm, I have chosen to state linewidths and Doppler shifts in picometers for convenience in this article. Sub-picometer shifts are insignificant.) Some lines lie close together, making broader dark bands. The lines are mostly in the visible region. The ones that correspond to absorption in the solar atmosphere are called Fraunhofer lines. The absorption is mainly by neutral or ionized elements, especially iron vapor.

The solar spectrum also contains many lines due to earth atmosphere absorption. These lines are of no help in reducing background, since they would also reduce signals transmitted through the atmosphere. They are distinguishable from solar lines because of the temperatures at which the absorbing molecules could exist. Water vapor, carbon dioxide, and diatomic oxygen are found in the earth atmosphere; solar absorbers such as iron vapor are mostly atomic. Solar molecules contain at most a few strongly bound atoms.

A detailed solar spectrum appears in Ref. 2. A sample is shown in Fig. 1, covering 529.1 nm to 532.4 nm. Most of the lines in the solar spectrum have been attributed to various molecules and radicals in Ref. 3. Consultation with that reference is necessary to be sure that the lines are Fraunhofer lines and not absorption lines in the earth's atmosphere.

One candidate wavelength for optical space communications is half that of a Nd:YAG laser, because of that laser's highly efficient use of power even after frequency doubling (Ref. 4). The halved wavelength with the next-to-lowest threshold corresponds very closely to the Fraunhofer line listed in Ref. 3 as centered at 530.7369 nm with an 8.6 pm width. The strongest cw laser wavelength, 1064.1 nm at room temperature, when halved falls into a region without Fraunhofer lines. However, if the YAG temperature is raised or lowered by about 20°C, the halved wavelength will fall either within the pair of singly ionized iron lines near 531.7 nm or the neutral iron line at 532.4 nm.

B. Fraunhofer Filter

A Fraunhofer filter consists of a multi-layer dielectric interference filter and a Fabry-Perot etalon. The theory of Fraunhofer filter design is reviewed in Ref. 5 and a practical example is described in Ref. 6.

By itself, the multi-layer dielectric filter may have a passband as narrow as 1 to 2 nm. Transmission may still be as good as 70%. Further attempts to narrow the passband of a dielectric filter would pay a high cost in reduced transmission.

The Fabry-Perot etalon consists of two parallel, flat, highly reflecting optical surfaces separated a distance d by a medium of refractive index n. Perpendicularly transmitted wavelengths are those which are equal to nd divided by any natural number. Transmission drops very rapidly as the wavelength deviates from a transmitted wavelength. As the wavelength continues to vary, it approaches the next transmitted wavelength and the transmission rises rapidly again.

Even a thin etalon has many passbands. The finesse (defined as the width-to-spacing ratio of the passbands) depends on the geometric mean R of the reflectivities R_1 and R_2 of the two surfaces ($R^2 = R_1 R_2$). This finesse may be degraded by surface imperfections, surface misalignment, and absorption on or between the surfaces.

When the multi-layer dielectric filter and the etalon are combined to make a Fraunhofer filter, the etalon spacing is chosen so that one of its passbands corresponds in center frequency and width to the desired Fraunhofer line. The multi-layer dielectric filter passband is also centered on the Fraunhofer line; its width is chosen only narrow enough to block the neighboring etalon passbands. The peak transmission of the multi-layer dielectric filter can be relatively high since its passband need not be very narrow. Overall transmission of a Fraunhofer filter may be 30% to 40%.

C. Tuning Methods

A Fraunhofer filter is tunable over a narrow range by varying the etalon refractive index or the spacing, or both. A solid glass etalon could be temperature-tuned by choosing a material such as Pyrex with a large coefficient of thermal expansion. Then d would increase with increasing temperature. Many glasses have large positive values of the rate of change dn/dT of refractive index with absolute temperature T. A glass combining a large coefficient of thermal expansion with a large positive dn/dT gives the greatest tuning sensitivity to temperature.

An etalon made from two optical flats with an air space between could be tuned sufficiently by fractional atmosphere pressure changes. The spacer thickness could be varied thermally or piezoelectrically.

Depending on the light entrance conditions, a designer might wish to hold the temperature, pressure, and spacing constant and tune the filter by tilting it.

III. Adaptive Compensation for Three Doppler Shifts

There are four objects involved in the analysis of background interference in an optical data link: the sun (⊙), the source (s), the body that appears in the background (b) of the source, and the receiver (r). Radius vectors from one of these objects to another may be distinguished by an ordered pair of subscripts indicating the tail and head of the vector. The relative line-of-sight velocity of body 2 with respect to body 1 is the component of the relative velocity along the line of sight:

$$v_{12} = \bar{r}_{12} \cdot \dot{\bar{r}}_{12} / (\bar{r}_{12} \cdot \bar{r}_{12})^{1/2}$$

The three velocity components that cause Doppler shifts are the sun-background velocity $v_{\odot b}$, the background-receiver velocity v_{br}, and the source-receiver velocity v_{sr}. In the vicinity of the solar system and on typical missions all these velocities are small compared with the speed of light c.

A signal frequency shift Δf_{sr} or a signal wavelength shift $\Delta\lambda_{sr}$ due to the Doppler effect and the line-of-sight velocity component v_{sr} between the source and the receiver is

$$\Delta f_{sr} = f_{sr} v/c$$

Also

$$(\Delta f_{sr})/f = -(\Delta \lambda_{sr})/\lambda$$

Other shifts are calculated with similar formulas using the appropriate subscripts.

When the background interference is reflected or scattered sunlight, the Fraunhofer lines of the sun will be reproduced in the spectrum of the background (provided the illuminated surface has no significant fluorescence). The wavelengths of the Fraunhofer lines in the incident light will be shifted up or down as the surface is moving toward or away from the sun. These shifts will be referred to as "incident Doppler shifts."

When the source is seen against a background, the wavelengths of the Fraunhofer lines in the background will suffer a second Doppler shift if the background surface is moving toward or away from the receiver. These shifts will be referred to as "reflected Doppler shifts."

The laser source wavelength will be Doppler-shifted up or down as the source approaches or recedes from the receiver. These shifts will be referred to as "source Doppler shifts."

The two background shifts, incident and reflected, add algebraically. The dependence of the sum on the velocity vectors between the sun and the surface, and between the surface and the receiver, is complicated. The source shift may not correspond to either of the background shifts or to their algebraic sum. Hence, if the source laser wavelength is to stay within a Fraunhofer line of the background, it will have to be tunable as the background changes. Tuning has the effect of making small color changes; thus the source laser must act like a chameleon, except that the reason for the color change is opposite to that of the chameleon. The chameleon changes color to make itself invisible against the background; the source laser changes color to make its signal visible.

The source and reflected background shifts will be identical unless the source and the background surface have different velocity components toward the receiver.

For instance, if a space probe has made a soft landing on a planetary or satellite surface, it shares the motion of the surface. Sunlight falling on the surface may be Doppler-shifted relative to the original solar wavelengths. If the source laser makes the appropriate chameleon tuning shift, the source wavelength will remain within the line whatever the motion of the receiver relative to the probe and surface may be. The receiver would merely tune its filter to the source wavelength it saw.

If the source is flying over the background, then its velocity component v_{sr} is in general different from the velocity component v_{br} of the background surface, both as measured from the receiver. The required chameleon tuning shift is $(1 + v_{br}/c)/(1 + v_{sr}/c) - 1$. Since all the speeds are small compared with the speed of light, this tuning shift is approximately $(v_{br} - v_{sr})/c = v_{bs}/c$. This means it would be sufficient for the source laser to tune itself to what it perceives as the center frequency of the background Fraunhofer line when measured from the spacecraft. It need not consider the velocity of the receiver. It only needs to know the direction of the receiver in order to look in the opposite direction and find out what the background is.

The receiver behavior is simpler. It needs only to tune to the received source wavelength. It may assume the source is centering its wavelength on the Fraunhofer line.

IV. Doppler Shifts for Typical Situations

For yellow light (500 nm, 5000 Å, 600 THz) a shift of 100 pm (0.1 nm, 1 Å, 120 GHz) corresponds to $v = 60$ km/s. A shift of 10 pm or 12 GHz, comparable with a single Fraunhofer linewidth, corresponds to $v = 6$ km/s. Shifts smaller than 1 pm would be negligible.

Solar system velocities arranged from largest to smallest are generally due to planetary revolution about the sun, satellite orbital revolution about a planet, and surface rotation of a planet. Many of these velocities are tabulated in Ref. 7. The effects of these will be considered first for the incident light, and then for the background and source shifts relative to the receiver.

A. Incident Shifts

Doppler shifts in the illumination from the sun would be zero if the planets were in perfectly circular orbits. In fact, all the orbits exhibit some ellipticity. At the apses (perihelion and aphelion) the Doppler shift is zero. The maximum Doppler shift occurs when

$$\cos E = e$$

where E is the eccentric anomaly, and e is the eccentricity. The maximum speed away from the sun is

$$v_{\odot b} = 2\pi ae/[P(1 - e^2)^{1/2}]$$

where P is the period of revolution, and a is the orbital semimajor axis. These speeds and the corresponding Doppler shifts are displayed in Table 1.

B. Background Shifts

Angular rotation rates follow no particular pattern in the solar system. Surface rotation velocities are the product of the angular rotation rate and the radius of the body, so they are large only for the largest bodies. The sun itself shows rotational Doppler shifts of its Fraunhofer lines near the equatorial limbs. No natural satellite and no terrestrial-like planet has a surface rotation velocity large enough to cause an appreciable Doppler shift. Equatorial velocities and corresponding Doppler shifts are shown in Table 2.

Sunlight falling on these planets would be shifted toward shorter wavelengths from the approaching limb, and toward longer wavelengths from the receding limb. Therefore, these incident Doppler shifts would only require an additional chameleon shift as the probe appeared to cross one of the planet limbs close to the equator.

If the probe made a soft landing on one of these planets near the equator, the required chameleon shift would be largest at local dawn or dusk. However, the apparent surface for a Jovian planet is really the top of the clouds. Even a balloon probe would rapidly sink out of sight of earth beneath them. Therefore, one need not usually consider a soft landing on any body large enough and rotating rapidly enough to have a significant rotational Doppler shift.

Objects too small to retain much atmosphere (Mars, Mercury, Pluto, natural satellites, or the asteroids) are usually too small to have appreciable surface velocity Doppler shifts, even if their rotational rates are large.

At times when a planet nears occultation by the sun, the radial component of its velocity relative to earth drops nearly to zero. Therefore, when a space probe is near or on a planet, and the line-of-sight to earth passes close to the sun, both the sun glare and the planetary background can be blocked by a Fraunhofer filter.

C. Source-Receiver Shifts

A space probe may have any velocity relative to the earth. However, it will seldom have another body as a background unless it is close to that body. It will stay close only if it has approximately the same velocity as the body. It is, therefore, nearly sufficient to analyze the velocities of the planets relative to the earth.

Planetary revolution velocities decrease inversely as the square root of the radius from the sun. The formula follows from Kepler's law:

$$\nu_{\text{planet}} = 2\pi\,(1\text{ AU})^{3/2}\text{ yr}^{-1}/(r_{\text{sun-planet}})^{1/2}$$

$$= (30\text{ km/s})\,(1\text{ AU}/r_{\text{sun-planet}})^{1/2}$$

The same formula applies for satellite orbital revolution about a planet, whether it is the receiver in orbit about the earth, or the signal source on a spacecraft in orbit about the target planet. The constant depends on the planet mass. Using the universal gravitational constant $G = 6.670 \times 10^{-11}$ N-m^2-kg^{-2},

$$\nu_{\text{satellite}} = (G\,M_{\text{planet}}/r_{\text{planet-satellite}})^{1/2}$$

The earth's revolution velocity causes almost the largest and also the most troublesome Doppler shift of all those that must be considered for optical communications. Fortunately, it is also nearly the slowest. The repetition cycle time is one year. Actually the repetition cycle time depends on the periods of both planets at the ends of the data link, but mostly it depends on the period of the inner planet. There are only two planets with shorter periods than earth's. The shortest repetition cycle time for a revolution Doppler shift is that of Mercury, 88 days. Rapid tuning of the filter is, therefore, not required for most projected missions.

The maximum radial component of the relative velocity between an inner and outer planet in circular orbits in the solar system is given by

$$\nu = \nu_{\text{in}}\,[1 - (r_{\text{in}}/r_{\text{out}})^{3/2}]$$

and the minimum is $-\nu$. The maximum occurs when the inner planet lags behind the outer planet by an angle whose cosine is $r_{\text{in}}/r_{\text{out}}$, and the minimum occurs when the inner planet leads by the same angle. See Table 3 for these velocities and Doppler shifts.

If the near-earth end is on a satellite, there are Doppler shifts due to the earth-orbital velocities. These shifts decrease with increasing satellite altitude. If tuning is required, its repetition cycle time corresponds to the orbital period. At the probe end, if the source is in an isosynchronous orbit, there can be appreciable Doppler shifts for the rapidly spinning planets beyond the earth. Refer to Table 4 for these velocities and Doppler shifts.

The surface escape velocity is just the square root of 2 times the orbital velocity of a satellite at negligible altitude. (Note that the Doppler shift for a satellite in low earth orbit is just the table entry for earth divided by the square root of 2.) These velocities are given for major bodies in Table 5. The Doppler shifts caused by these velocities affect optical communications only during the descent or return phases of a mission to the surface of a planet.

V. Conclusions

Fraunhofer filters can improve optical space communications. It is possible to find a close match between a Fraunhofer line and a useful laser wavelength. Laser wavelengths and Fraunhofer filters can be tuned to match shifts in the Fraunhofer lines due to the Doppler effect. Typical Doppler shifts are less than 50 pm (0.5 Å) or 60 GHz for almost all missions outside the orbit of Mercury at almost all times. Doppler shifts have been calculated for many situations to aid designers who would use either a Fraunhofer filter with direct detection or heterodyne detection with a reasonably narrow post-detection bandwidth.

References

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Table 1. Doppler shift of solar illumination at epoch of maximum speed away from the sun

Planet	Maximum speed, km/s	Doppler, pm	Doppler, GHz
Mercury	10.06	18	-18.9
Venus	0.24	0	-0.4
Earth	0.50	1	-0.9
Mars	2.26	4	-4.3
Jupiter	0.63	1	-1.2
Saturn	0.52	1	-1.0
Uranus	0.31	1	-0.6
Neptune	0.04	0	-0.1
Pluto	1.21	2	-2.3

Wavelength (nm): 532.05
Frequency (THz): 563.5

Table 2. Equatorial limb velocity doppler shifts

Body	Equatorial speed, km/s	Doppler, pm	Doppler, GHz
Sun	2.1	4	-3.9
Earth	0.5	1	-0.9
Mars	0.2	0	-0.5
Jupiter	12.7	22	-23.8
Saturn	10.3	18	-19.4
Uranus	3.9	7	-7.3
Neptune	2.5	4	-4.7

Wavelength (nm): 532.05
Frequency (THz): 563.5

Table 3. Maximum radial component of velocity relative to earth, for circular orbits

Planet or radius of planetary orbit	Max relative speed, km/s	Doppler, pm	Doppler, GHz
5 solar radii of sun	194.5	345	-365.6
10 solar radii of sun	136.7	243	-256.9
Mercury	36.3	65	-68.3
Venus	13.5	24	-25.4
Earth	0.0	0	.0
Mars	13.9	25	-26.2
Jupiter	27.3	48	-51.3
Saturn	28.8	51	-54.1
Uranus	29.4	52	-55.3
Neptune	29.6	53	-55.6
Pluto	29.7	53	-55.7
Infinity (ecliptic)	29.8	53	-56.0

Wavelength (nm): 532.05
Frequency (THz): 563.5

Table 4. Isosynchronous orbit velocities and doppler shifts

Body	Altitude, km	Orbital speed, km/s	Doppler, pm	Doppler, GHz
Sun	24055600	73.2	130	-137.6
Mercury	237301	0.3	1	-0.6
Venus	1534720	0.5	1	-0.9
Earth	35775	3.1	5	-5.8
Mars	17032	1.4	3	-2.7
Jupiter	89304	28.2	50	-53.0
Saturn	50964	18.6	33	-35.0
Uranus	36938	9.8	17	-18.4
Neptune	59504	9.1	16	-17.1

Wavelength (nm): 532.05
Frequency (THz): 563.5

Table 5. Surface escape velocities and doppler shifts

Planet or satellite	Escape speed, km/s	Doppler, pm	Doppler, GHz
Mercury	4.2	7	-7.8
Venus	10.4	18	-19.5
Earth	11.2	20	-21.0
Moon	2.4	4	-4.5
Mars	5.0	9	-9.5
Jupiter	60.2	107	-113.2
Io	2.5	4	-4.6
Europa	2.1	4	-3.9
Ganymede	0.9	2	-1.7
Callisto	2.0	4	-3.8
Saturn	36.1	64	-67.8
Titan	0.8	1	-1.5
Iapetus	0.7	1	-1.3
Uranus	22.2	39	-41.7
Titania	0.7	1	-1.4
Neptune	24.5	44	-46.1
Triton	3.1	6	-5.8
Pluto	5.0	9	-9.4

Wavelength (nm): 532.05
Frequency (THz): 563.5

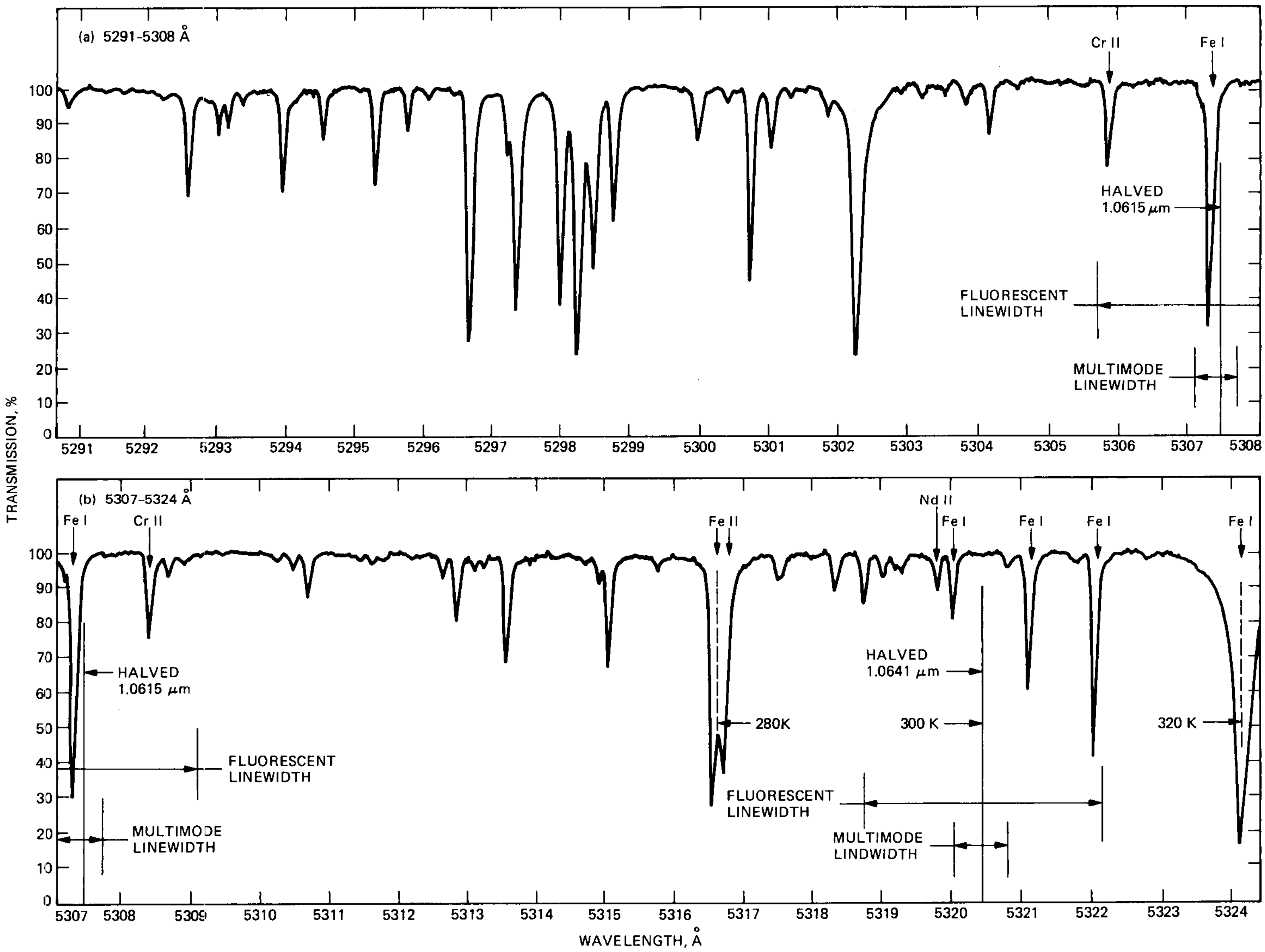

Fig. 1. Solar spectrum from 5291 to 5324 Å